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GRANITE AND METASOMATISM

REGINALD A. DALY

ABSTRACT. All geologists interested in the genetic problem of granite have long agreed that some granites crystallized from their own melts (magmas), while other rocks of closely similar composition and texture were formed by molecular replacement (metasomatism) of older, non-granitic rocks by absorption of foreign material. According to the cumulative opinion of most experienced geologists during the past hundred years, the ratio of total volume of "magmatic granite" to total volume of "metasomatic granite" in the earth's crust is large. Within the last twenty-five years a smaller but increasing number of workers, here called for convenience "metasomatists," have come to prefer a reversed ratio. The following paper is intended to show that the second group has not thought "to scale," have neglected many vital facts bearing on the problem, and have in no wise weakened the arguments of the "magmatists," which have led toward what appears to be a sound theory of the evolution of the earth's crust.

INTRODUCTION

POSED more than a century and a half ago, the granite problem is one of peculiar dignity and meaning. If it were solved, the origin of basalt, peridotite, anorthosite, gneiss, and other principal stuffs of the earth's crust would be more intelligently discussed, and theories relating to continental genesis, geophysics, ore genesis, geodesy, physiography, oceanography, and paleontology would be better controlled. If it were solved, man would know with more assurance why there is dry land, a perch for air-breathers like himself; how he can thrive in a metal-hungry age; and how to account for the sedimentary rocks which bear the medals of creation and declare so much of the history of our planet. But there are two general and portentous difficulties in the way when the attempt is made to round out a good theory of granite itself.

First, the solution cannot be complete until the cosmogonists declare the mode of birth, the initial temperature, the initial composition including gas-content, and the youthful organization of the nearest of the heavenly bodies; here geologists lack some of the guiding data they need.

The second lion in the way toward the desired goal is an ineluctable necessity. No solution of the granite problem is possible until there be assembled and digested the relevant facts recorded by polyglot field-workers in seven continents and the wide oceans. But even this world-wide, encyclopedic product of field work with hobnails, hammer, compass, and topographic map is manifestly insufficient. Other data, also widely scattered in the great libraries, must come: (1) from properly designed experiments on melting, molten, and freezing silicates and mixtures of silicates, even if only in "little crucibles"; (2) from analogies secured by experiments with materials other than silicates; (3) from handbooks of the skilled petrographers; (4) from information supplied by seismograph and gravity pendulum; (5) from any appropriate hints by astrophysicists and cosmologists; and (6) from the results of those writers who used well regulated imagination when they delved into the depths of both space and time.

Thus the granite problem demands scholarship of dismaying breadth and thoroughness as well as vision regulated by common sense. To make the best interpretation of what is both figuratively and literally a world of facts and suggestions is not science; it is rather an art, a way to science, and subject to the personal handicaps of the artist. Anyone offering a solution should be wise enough to know that his own building is in part merely a scaffolding around the temple of truth. Life is short; art is long!

Hutton showed how wrong was Werner's guess that granite was a precipitate from a primeval ocean, a world-circling "chaotic fluid." Ever since, most geologists have favored the idea that nearly all massive granite represents former magma, a melt, which during its crystallization lost some of its initially small content of gas and vapor. No widely experienced petrologist doubts that some granite-like rocks are products of metasomatism of sediments and schists, that is, the products of mineralogical change wrought by the introduction of thin, exotic, highly mobile fluids ("emanations") containing the elements of quartz and feldspar and imbibed by the invaded rocks. For a century the ratio of volume for such metasomatic granite to magmatic granite in the earth was steadily regarded as small. But during the last twenty years geologists and petrologists of increasing number have come to prefer a reversed

ratio. Their doctrine of molecule-by-molecule or atom-by-atom deposition of matter essential to granite by "emanations" originating at depth, and in quality sufficient to have made most of the quartz-rich massive rocks of the world, is a kind of inverted Wernerism.

However, upholders of the new doctrine believe it possible that the energized "thin" fluids have here and there fluxed originally solid rock, with the development of true magma which has been capable of eruption in the form of bodies of "young" granite as well as bodies of rhyolite and obsidian. These exponents also recognize that partial fluxing of the kind may have made the invaded formations mobile and thus able to intrude higher levels of the earth's crust; and they also assume that during orogeny the lower part of the planet's Sial or "granitic layer" may, because of its forming part of the depressed mountain-root, have been thoroughly melted and eruptible.

Thus, while they differ about the ratio of volume of metasomatic granite to volume of magmatic granite, the two schools of thought have some common ground. This fact suggests the possible value of a convention adopted for brevity of reference and perhaps for clearer understanding of the text to follow. The convention: those who stress solidification of melts will be called "magmatists," and those who stress molecular replacement and addition of material will be called "metasomatists." The quotation marks will indicate the arbitrary character of the naming. Most writers belonging to each of the two schools emphasize the rise of matter from the depths. However, some "magmatists" prefer a two-way street, the sinking as well as the rising of material being essential in the development of granitic bodies. With one exception the "metasomatists" prefer a one-way street and the uprise of material. The "magmatists" demand temperature of 1000°C. or higher in the development, while the "metasomatists" accept much lower temperature for their emanations when still effective in the making of granite.

Another expression, also to be distinguished by quotation marks, will be convenient for present use. It is "granite" (with adjective "granitic"), intended to cover the massive quartz-rich types of rock—granodiorite, quartz monzonite, quartz syenite, tonalite, and quartz diorite, which each of

the two schools explains in a manner similar to that preferred for granite proper.

The object of this paper is to list some principal reasons for the writer's belief that the "metasomatists" have overstated their case, and this because as individuals and as a group they have neglected vital facts. The grounds for his belief will appear as the discussion deals with: (1) the assumed emanations or granitizing agents; (2) the phenomena of the vast display of "granite" in the Pre-Cambrian "shields," which seem to represent fairly well the greater part of the Sial or "granitic layer" with minimum average thickness of ten kilometers; (3) the nature of a basaltic earth-shell, still deeper, which must be in close genetic connection with the formation of the Sial itself; (4) the associated questions arising from the facts known about the composition and volume of the ocean; and (5) alternative method or methods by which any large body of "granite" won space for itself in the earth's crust—a question which the "metasomatist" Read (1948, p. 7) has described as "at the heart of the granite problem," and a question particularly intriguing to any geologist who studies post-Cambrian batholiths and stocks in the field.

MODE OF ATTACK ON THE GRANITE PROBLEM

To estimate the volume-ratio of magmatic "granite" to metasomatic "granite" is necessarily a matter of theory. A good theory must rest on facts derived from observation at the earth's surface and just as obviously on assumptions about conditions in depth when "granites" were made.

At the outset it is expedient to weigh some fundamental considerations. The first of these is dry land of continental dimensions, dry land dominantly surfaced by "granite" or by the chemically equivalent acid gneisses or by the debris of "granite" and gneisses. A second fact is proof that the velocities of the earthquake waves are those expected if closely similar acid rock underlies the continental surfaces to average depth of at least ten kilometers. Geophysicists have established a third fact, that this interrupted earth-shell, the Sial, is in quasi-flotation on the earth's body because of the relatively low density of the patchy shell. The geologists have proved a fourth fact—that long before the Paleozoic era extensive dry-land masses of Sialic or dominantly "granitic" composition were

eroded in some regions and veneered with quartzose sediments in other regions. The evidence for this comes from all of the existing continents. It seems therefore clear that more than 95 percent of the world's "granite" was formed far back in Archean time. And there is a fifth fact of the first rank: "granite" made in post-Cambrian time is chiefly batholithic and almost entirely confined to belts of post-Cambrian mountain-building, which themselves are located in the Sial, whether emerged or covered by the ocean.

The discussion of origins for both Sial and the comparatively young batholithic masses is laden with difficulties. We do not know the initial temperature and gas-content of the earth. We do not know whether the Moon is wholly or in part of terrestrial origin, though, if it was, the forceful ejection from one hemisphere might have produced a strong contrast of both material and temperature of the robbed hemisphere with the material and temperature of the opposite hemisphere. We do not know how effective was the Moon, supposed to be a daughter of the earth and initially close to the earth, in slowing down the planet's rotation and thus threatening the stability of the original crust of the planet by fracturing. We do not know with absolute certainty the heating power of radioactivity in the earth-shells.

Thus a speculator has to cut a number of Gordian knots before he can make any real progress toward explaining the Sial, the real "heart of the granite problem." With full consciousness of arbitrary procedure the writer does some cutting. Specifically he does not assume the temperature of the earth's outer shell in pre-Archean time to have been high enough for unmixing of a granitic layer from a basaltic layer —a conception founded on Fenner's (1948) idea of such immiscibility even in post-Cambrian time. Encouraged by the opinion of petrologists in general, the present writer assumes that important superheat does not now characterize, and perhaps has never characterized, the superficial earth-shell. He assumes that the heat of radioactivity is, and has been, steadily developed in the globe. Further, he is quite prepared to entertain the hypothesis that from the depths of the young earth steam and other gases emanated toward the surface at a rate higher than that ruling since Archean time. Therewith he finds one reason why the Archean terranes exhibit so much

local metasomatism. On the present occasion he does not assume any particular thermal gradients for the earth-shells beneath the basaltic shell whence have come the basaltic lava-floods at intervals since early Archean time. He assumes that the crystallized Sialic material, if in average no more basic than granodiorite, is gravitationally stable on an underlying layer of liquid basalt. On the other hand, he assumes that, because of density difference, crystallized Sial is liable to founder in granite magma and in Sialic magma generally; also that crystallized basalt and even other somewhat less basic but crystallized rocks are liable to founder in liquid basalt. He assumes the sinking of early-formed crystals in and from either liquid. Finally, he assumes that sunken blocks are partially remelted, with the result that the more salic, lower-melting part of each rises toward the earth's surface, there being a tendency to form ultimately within the composite magma a top layer of granitic composition.

Although the "metasomatists" recognize the five great facts above listed, no member of the group has given the five all the attention they deserve in our problem. Largely because of this limited outlook the arguments for the wholesale molecular replacements have been based on widely different assumptions. The wide range of differing and competing premises essential to their scheme, is of itself ground for doubting the logic of any or all of their school of thought. Their ideas about source, chemical nature, and mode of travel of the emanations will first be examined. Then the origins of the Sial and of the post-Cambrian batholiths will be considered, when it will be found that the "metasomatists" are vague also about their second necessary premise, namely, the original character of the rock matter supposed to be molecularly replaced. Further evidence that those writers have not thought through our problem appears when the history of the basaltic earth-shell and also the composition and volume of the ocean are incidentally discussed. Thus again and again we shall see the "granite" problem is planetary and not to be solved by ordinary geological field-work.

THE "EMANATIONS"

Before taking a closer look at the arguments of the "metasomatists" it is well to note that Sederholm and his followers as well as Michel Lévy and Lacroix, all of whom

by their combined researches demonstrated granitization on a comparatively large scale, are not to be classed among the "metasomatists" as above defined. For all of those Fennoscandian and French masters the source of the granitizing solutions was granitic magma. All of them were quite clear about the relative volumes of granite magma and corresponding granitized rock—clear as to which was the hen and which the egg. Equally obvious to them was the illogicality of seeking the origin of "granite" in the molecular transformation of shale, phyllite, mica schist, and quartzite, since these are chiefly detrital from "granite." All of these experts in petrogenesis were incapable of reasoning in a circle. The "metasomatists" of the present day are, therefore, not entitled to claim from these Fennoscandian and French studies any support for the idea that metasomatic "granite" dominates in the earth's crust. We may now return to the logical difficulties in the way of accepting the extreme ideas of the new school.

(1) Divergence of views about the source of the supposedly potent emanations is clear. Backlund (1936, p. 343) and MacGregor and Wilson (1939, p. 201) find a source in the solid rocks adjacent to the transformed body. Reynolds (1947, p. 222) finds there the principal source. MacGregor and Wilson (1939, p. 201), like Barth (1936, p. 830), find another source in the earth's granitic layer, the Sial. Barth (1939, p. 111) finds a source in the liquid residual from the advanced crystallization of a basaltic layer beneath the granitic Sial. Rittman (1939, p. 603) specified as source an olivine-basalt layer of great thickness and resting on a much denser planetary core. Holmes (1948, p. 414), Wegmann (1935, p. 345), van Bemmelen (1940, p. 33), and King (1947, p. 37) find the principal source at "great depth," but do not declare the nature of the parent earth-shell or earth-shells. Termier (1912, p. 592), who had recommended that the deep interior of the globe be left "aux poètes," has since written his eloquent prose to advocate colossal metasomatism and granitization by his "colonnes filtrantes" coming from great depth.

(2) Sederholm and Michel Lévy used field evidence rather than psychological necessity when they derived their granitizing solutions that bore silica and the oxides of both plagioclase and orthoclase dissolved in enough water to make the solutions "thin." Many of the more thorough-going "meta-

somatists" of the last twenty years describe the solutions as containing the oxides "needed" or "wanted" to give solid "granite" by molecular transformation of solid rocks. Since the latter include such differing types as pelites, mica schists, amphibolite, greenstone, diabase, gabbro, and limestone, the named oxides in the assumed solutions are those "needed" or "wanted" to make the "granites" whose development is being sought. Soda, silica, and lime are the oxides most commonly named, but seldom potash, which is nevertheless so important, so "needed," in the supposed granitization of limestone, greenstone, amphibolite, and basaltic rocks. In general the potash should be at least as abundant in the solutions as soda, and yet it is still to be shown why any emanation, especially one from great depth, would carry comparable proportions of the two alkalies.

Thus it is not easy to picture what the "metasomatists" mean when they write of the chemistry of the emanating solutions. Until there is clearer statement of the composition of these in terms of all the oxides and elements present, their argument for the extreme metasomatism must be regarded as weak in its second fundamental premise. Meantime specific mention of the oxides "needed" or "wanted" for granite-making might be readily taken as the product of reasoning in a circle so far as the chemistry of the postulated emanations is concerned.

One's mental trouble is not assuaged by Rittmann's (1947, p. 11 and 14) description of the granitizing agent as "gas," without his giving the composition of this gas. Nor is there any clear statement of the total composition of the rising "clouds" of ions or atoms, which, according to some "metasomatists" writing in the last dozen years, are to be preferred as the transformers. The nearest approach to such a statement appears to be that of Barth (1947, p. 181), who, though not to be classed as a full-fledged "metasomatist" as above defined, has discounted Sederholm's theory of transformism and now explains large bodies of Pre-Cambrian granite in Fennoscandia by the atomic-cloud hypothesis. For Barth each rising "cloud" is an "ichor," this term here meaning something quite different from that assigned by Sederholm, its inventor. Barth holds that his own "ichor" has produced two kinds of granite, one represented by molecularly replaced older rocks

and the other represented by direct crystallizations of the atomic-cloud itself. This "ichor" is supposed by him to come from great depth. But we note again that the geophysicists are unanimously insistent on the comparatively minute proportion of potash in the deep earth-shells, and that no process of increasing the proportion of the oxide in rising emanations has ever been announced by the "metasomatists." Their dilemma is all the more apparant when we take into account a principle stated by Lapadu-Hargues (1945, p. 299), one of them, namely that the mobility, migratory power, of the atoms is proportionate to the diameter of the ions concerned, so that Na and Ca, already at depth in decided excess over K, should outstrip K in the rise toward the earth's surface. In striking contrast is the view of King (1947, p. 56) that potash travels farther than soda for example and is consequently "fixed at greater distances from source than the soda emanations."

(3) To transform a heterogeneous mass of quartzose sediments, limestone, and basic rocks into homogeneous "granite" by molecular replacement demands the expenditure of much energy, particularly thermal energy. Since, according to the "metasomatists," the visible parts of the young batholiths of the orogenic belts were so developed close to the earth's rocky surface, the granitizing agent must have brought up most of the heat required for the postulated chemical reactions. Few estimates of the agent's temperature when rising to the appropriate levels have been published. That inferred by Ramberg (1946, p. 29), when in his view Pre-Cambrian limestone was granitized, was no higher than 350°C. From other Pre-Cambrian cases Backlund (1936, p. 343) assigned "moderate" temperature, "far below the melting temperature" of ordinary rock. From Norwegian cases Barth (1929, p. 122) deduced a temperature under 500°C. for the granitizing solutions. Holmes and Reynolds (1947, p. 61), preferring an agent composed of "clouds" of ions, inferred quite moderate temperature for the reason that "ionization attains a maximum at a little above 200°C." and "at higher temperatures it begins to decrease again."

None of the four estimates is accompanied by a statement as to the depth at which the molecular transformation was effected. Presumably the emanations were much hotter before

they began to rise from "great depth." On that assumption and because the rocks invaded at "great depths" were also hotter, some "metasomatists" like to think of the granitizing reactions as having taken place after the invaded formations had been orogenically depressed to depths much greater than those ruling in the uppermost part of the earth's crust.

Clearly, the "metasomatists" are not agreed about the third premise basal to their logic—that of securing sufficient energy for the making of large masses of "granite" according to their recipe.

(4) Nor are they of one mind about the mode of upward diffusion of the emanations. One of their groups favors upward migration along the mutual contacts of the minerals composing the invaded rocks. A second group favors solid diffusion, the emanational matter being ionic and rising through the space lattices of the crystals in the invaded terrane.

That the first group has been on the wrong track in its thinking is shown by Holmes and Reynolds (1947, p. 50ff), who themselves are "metasomatists" and belong to the second group. They point out that "the essential functions of gaseous or liquid solutions at any particular spot are to bring up the incoming ions and maintain their concentration, and to carry away the displaced ions. As between liquid or hydrothermal solutions and gaseous or pneumatolytic solutions, it seems probable that these functions could be carried out more effectively by the former."

Continuing, their summary statement reads: "A gas phase would have the advantage of easy penetration along submicroscopic cracks through otherwise impermeable rock, but against this it suffers from several disadvantages. Considerations of relative volatility suggest that a gas phase is most likely to be acid. In the replacement phenomena under discussion, however, the evidence is overwhelmingly suggestive of the dominance of alkaline materials. Moreover, components of widely different volatility would need to be combined in the migrating stream . . . Ingerson and Morey cite experimental observations indicating that diffusion through gas is quantitatively a more effective process than transport by gas . . . . There is the third difficulty that the degree of ionisation of a concentrated gaseous solution under high pressure and therefore of relatively high density is likely to be extremely low.

A gas phase is therefore thought to be a feeble carrier of the ions necessary to initiate solid diffusion through the crystals with which it comes into contact. Crystal linings along the surfaces of rocks and drusy cavities (rather than metasomatic replacements) are the characteristic results to be expected from gaseous transport and deposition.

"On the other hand, hydrothermal solutions, if of magmatic ancestry, are likely to be strongly alkaline from the start, as a result of hydrolysis of silicate minerals. They are also likely to have a higher degree of ionisation . . . . In respect of both composition and degree of ionisation hydrothermal solutions appear to have a definite advantage over gaseous solutions, especially in their capacity for initiating and maintaining metasomatic replacements of appropriate parageneses. But except where adequate passage-ways are available, e.g. by way of open cracks and fissures, their capacity for penetrating rocks is severely limited. Silica-bearing solutions in particular seem to have a very small power of soaking through rocks, like quartzite, in which the only passage-ways are the minute interstices between closely fitting mineral grains."

These authors therefore conclude that, since the interstices are isolated and discontinuous, "molar transport becomes impossible, and replacement can then be effected by means of solid diffusion.

"Applying the above and other relevant considerations . . . . it can be said that the few criteria available for discrimination suggest that solid diffusion was probably the dominant process concerned."

"It is impossible in a limited space to discuss the matter systematically, but to us it seems manifest that the whole process is more elegantly explained by progressive solid diffusion due to migration of ions through the crystal lattices and along the crystal boundaries."

Other writers regarding solid diffusion as the principal mechanism in granitization include Backlund (1936, p. 343), Ramberg (1948), Perrin and Roubault (1939, p. 64), Bugge (1945, p. 46), and Barth (1947, p. 181). All have rejected "ichors" as solutions. All are in duty bound to show how "clouds" of ions can make nearly or quite homogeneous "granite" in masses kilometers in thickness by diffusions into and

through the crystals constituting a highly heterogeneous terrane. To discharge that duty they have assumed an enormously energized condition of the "clouds" as they start up their long upward journey, but they are far from having explained how enough of this initial energy could be retained to permit the transformism at such high levels as those near the roofs of batholiths. Neither have the diffusionists paid adequate attention to the loss of chemical potential as each "cloud" works its arduous way upward. With each centimeter of advance the "cloud" must rapidly lose its chemical potential also. Moreover, these writers have overlooked the fact that the time during which a Cordilleran batholith was formed was finite; one might well ask: which would win the race, transformism or the inevitable cooling with loss of transforming power? Is there a clear answer to that question?

A more authoritative, though in principle similar, criticism of reliance on solid diffusion in the "granite" problem was voiced at the Ottawa symposium by Bowen (1948, p. 81).

Since the day-long discussion at Ottawa saw its way into print, Ramberg (1948), a solid diffusionist, has tried to account for the upward migration of the granite-making ions. He assumes the active force to be gravity, which has caused the light, granite-making ions to rise and the "unwanted" heavier ions to sink—a case of separation and double migration. To the present writer this reliance on tractions due to the differing weights of almost infinitesmal particles inside each of a multitude of crystals is a reductio ad absurdum in the theory of solid diffusion.

To conclude: while every experienced geologist cannot doubt the rise of emanations and also the fact that rocks and minerals including ores have been modified as well as replaced by solid diffusion, neither of these actions can with good reason be thought responsible for the emplacement of the huge batholiths. In this whole matter of emanations the "metasomatists" should try to reconcile premises and lines of reasoning and, above all, to think to scale! That they have overshot the mark is still more evident as we leave the field of physical chemistry and proceed to review facts which geologists have brought home in their note-books: facts concerning the Sial as well as the "granites" of the post-Cambrian chains of mountains.

THE SIAL OR "GRANITIC LAYER"

The following brief discussion of the outer earth-shells will be preceded by a few words devoted to some questions about the interior of our planet, particularly with regard to the possibility of a superheated, vitreous state for a large part of the silicate mantle on the iron core.

Some cosmogonists are inclined to look on meteorites as giving a clue to the composition of the earth, to regard this a daughter of the Sun, and to assume an initial temperature for the planet to have been so high as to compel a molten state from surface to center. These authorities recognize immiscibility of metallic, nickel-bearing iron with the silicate material and an early gravitational separation of an iron core from its thick silicate mantle. The rate of such settling-out of the iron must have been progressively lowered as the depth increased. The enormous increase of viscosity with increasing pressure may conceivably have prevented complete separation of small droplets of iron at great depth, even after the lapse of three billion years. Moreover, there is no certainty that such high pressure did not affect the degree of immiscibility. Hence, for those reasons alone, it seems possible that the mantle never reached chemical homogeneity, thus permitting convection currents from top to bottom of the mantle. If this should have been the case, a further possibility would have to be faced: some superheat at depth. On the other hand, at and near the surface, where viscosity was low, the silicate mantile could have been thoroughly cleansed of metallic nickel-iron. There, to the depth of perhaps one or two hundred kilometers, the material can be thought to have speedily attained the composition of the iron-free meteorites, that is, a peridotite. On this assumption may be based a speculative origin for a world-circling Sial.

Jeffreys (1929, p. 138) has pictured for the infant earth a complete settling-out of the metallic iron, leaving a peridotitic mantle about 3000 kilometers thick and so homogeneous as to permit complete convective overturn of its matter, with rapid chilling, and consequent freezing of the whole thick shell. By postulating such crystallinity he considered that he could best explain the transmissibility of the shear (rigidity-controlled) seismic waves throughout the mantle. But Bridgman's (1931,

p. 340 and 1949, p. 117) experiments on the remarkable effect of high pressure on the viscosity of both liquids and gases suggest the possibility that much, if not most, of the earth's mantle may be so viscous as to behave like a crystalline solid with respect to the deforming forces connected with either earthquakes or the variation of latitude.

In his own thinking about the early differentiation of the material of the infant, star-born earth, the present writer finds it easier to assume an initially molten state for the superficial peridotite. At the temperature of about 1400°C. radiative chilling would have been extremely rapid, so that before crystal-fractionation could get under way the surface material might have been crusted to small depth—tens of meters. Following Thomson's (1883, p. 483) speculation of long ago, one should expect instability, breakup and foundering of the new crust in the thick, less dense magma beneath; some remelting of the fragments in the hotter liquid; the rise of the lower-melting, less femic material; renewed crusting and foundering, with a tendency to develop a temporarily-liquid basalt at the surface. The same result would be expected if the high-melting olivine and bronzite or hypersthene, as free individualizations, sank because of their relatively high density. By integration of both effects one can conceive that a world-circling layer of molten basalt, several tens of kilometers thick, was developed.

The molten basalt would, however, be unstable chemically. It, too, would be affected by crystal-fractionation. With a composition possibly a little more salic than the plateau-basalt of post-Cambrian eruptivity, a five-kilometer or six-kilometer, world-circling, superficial layer of material chemically close to granodiorite might result. Such differentiation can be most readily understood if it too was a step-by-step process, involving repeated crustings, repeated founderings, and repeated remelting of sunken crust-blocks. The ultimate product would thus be an unsinkable "granitic" crust resting on a layer of slowly cooling and crystallizing basalt in which the intrinsic density increased with depth so as to ensure the inner stability of this sub-layer also.

At the Ottawa symposium Bowen (1948, p. 82), leading "magmatist," did not mention the Sial or the earth's "granitic layer" and stated that the batholiths "represent the great bulk

of our granites." Read (1948, p. 4), leading "metasomatist," spoke of an original granitic layer and again of "a light granitic sialic layer" overlying a denser, basaltic, Simatic layer in the earth, both layers having been formed when the planet was new. He gives no opinion as to how much of the less dense shell is true granite and how much consists of other kinds of "granite." Both of the leaders approve of the conclusion of the geophysicists who have found the upper Sialic part of the earth's crust in continental areas, to an average depth of 10 or 12 kilometers, to be "granitic." Read (1948, p. 5) seems to agree that this top sublayer was, in pre-Archean time, magmatic though even then of granitic composition. Is he, then, logical when he claims that most of the world's granite is metasomatic and that the problem of its development is a matter to be dealt with by field geology? Can the unaided field geologist deal adequately with an earth-shell so largely invisible, inaccessible?

Perhaps some "metasomatists" prefer to think of the young earth's crust as having been made of crystallized basalt or even more basic material and in pre-Archean time granitized by emanations from depth in volume to match the volume of the existing Sial. No one of their school, however, has developed the hypothesis so far as to imagine the fate of the enormous volume of material corresponding to the "basic fronts," or has deduced the effect on the volume and composition of the ocean. Any "thin" solution, representing a postulated emanation would presumably have been made "thin" by abundant water. In that case the extra silica and potash required for the granitization would be, by weight, only a small fraction of the hydrous solution, which itself was a small fraction of any earth-shell where the emanation originated. To develop a world-circling "granitic" layer only five or six kilometers thick would doubtless give an ocean several times as voluminous as that now existing. Also in all likelihood the salinity of this watery envelope would not be readily reconcilable with Clarke's (1916) careful accounting for the salinity of the existing ocean.

If the emanating solutions came from depth greater than the top of the peridotitic earth-shell, now apparently less than 80 kilometers below the surface, the basalt extruded during the formation of the Sial would, by the metasomatic hypothesis,

differ chemically and decidedly from the basalt extruded in post-Archean time. Yet there is a high degree of uniformity for the basaltic lavas emitted ever since an early Pre-Cambrian epoch.

If the solutions came from such depth the transition from the Sialic layer to the layer just below it should be gradual, but some seismologists, like Gutenberg, believe the mutual contact to be relatively sharp.

The same failures to account for relevant and more or less assured facts mean as many grounds for rejecting the hypothesis of upward-migrating "clouds" of ions. Ramberg's speculation does avoid the observational difficulties by sinking the heavier ions, but, as already observed, gives an incredible picture of the way in which diffusion can change the chemical composition of any rock.

Other objections to the "metasomatic" doctrine are indicated by the proof of both seismologists and geodesists that the Sial is now largely restricted to one hemisphere. The cause of the restriction is one of the most horrendous mysteries of earth science, one not to be discussed in the present paper. But the fact is beyond cavil and of critical importance. Since the "metasomatic" hypothesis, expressed in any of its chameleon forms, recognizes no need for the emanations to choose some routes upward rather than others, the hypothesis is quite unable to account for the utter lack of granite or rhyolite within the Sial-free earth-sector capped by the deep Pacific ocean, which covers nearly one quarter of the globe. No fragment of either type of acid rock has been found in the countless basaltic flows, and no Sialic mass has been indubitably found in this sector by the seismologists.

A related fact: If the postulated emanations have been so potent as to develop the batholiths of the post-Cambrian orogenic belts, one would expect that in some form or other three million square kilometers or more of the Canadian Archean Shield should exhibit on its anciently-peneplained surface some signs of similar upward invasion; yet no tell-tale sign of new granitization since the late Archean has been found in this vast area.

Read (1948, p. 7) regards "the problem of room" as lying at the heart of the granite problem." He doubtless had in mind the batholiths and stocks of the post-Cambrian orogenic

belts. How space for these bodies was secured is truly a vital question, to be later considered. It does not seem to be anything like so difficult to answer in the case of the granite of the Sial, if, as prompted by a reasonable guess, this layer was originally world-circling. Whatever the processes responsible for that vast granite-making, they had "all outdoors" in which to carry on their constructive work. If, on the other hand, the "granitic layer" was formed almost wholly in one hemisphere the colloquialism would not be strictly true. In either case the emplacement of the Sialic granite would not have involved the same kind of structural problem as that so insistent at post-Cambrian batholith or stock. Yet this conclusion does not conflict with the idea that molar movements were essential for the development of both Sial and batholithic bodies.

The writer also holds the opinion that the areal restriction of the Sial is not easy to reconcile with the view of a "magmatist" who believes each body of "granite" to be a direct, single-step differentiate of basaltic magma. During the long lives of the Hawaiian volcanoes the basaltic magma below their vents was chilled countless times to temperatures below which crystal-fractionation should, by theory, have produced "granite" or its effusive equivalent. Yet neither of these rock types has been discovered in the thousand-mile chain of islands. The same is true for some other volcanic piles of the central Pacific. Again, if the basaltic magma under the Canadian "shield" has been slowly freezing since late Pre-Cambrian time, with the direct formation of a corresponding amount of "granitic" differentiate, some of this relatively light material should have risen to the surface or to crust-levels reached by erosion. But there is no record of such upsqueezings since the beginning of the Paleozoic era.

Nor is it likely that the material of the Sial could represent the residual liquid resulting from the crystal-fractionation of a peridotitic earth-shell in a single step. The writer's doubt on this point is based on an application of the Clausius-Clapeyron equation connecting pressure with the temperature of freezing. From this relation it appears that the granitic residuum of crystallizing peridotite would be itself pressure-crystallized before it could be squeezed out of a peridotitic layer with top 40 kilometers or more below the earth's surface.

In view of the geological facts and of theoretical considerations the writer favors the conclusion that the Sial, containing the bulk of the world's granite, was evolved during pre-Archean or early Archean time, and that this layer as well as bodies of post-Archean "granite" were formed by successive founderings, successive remeltings in depth, and successive increases in the acidity of the upsqueezed, relatively light differentiate.

Considering the complexity of the whole process, it is reasonable to suppose that the young "granitic" crust would include rock types ranging from quartz diorite to granite proper as well as bodies of basaltic material which invaded the evolving Sialic crust from time to time. Thus speculatively the primitive Sial covered all the earth. How it could have been driven or pulled into the existing "land hemisphere" is a profound puzzle for "magmatist" and "metasomatist" alike. In whatever way the areal restriction was accomplished the variety of rock types might well have been increased by the action but without changing the essentially "granitic" nature of the layer, a character persisting to the present day.

METASOMATISM IN THE BELTS OF POST-CAMBRIAN OROGENY

We shall now consider the big cross-cutting masses of "granite" with no visible floors which center in the post-Cambrian mountain chains. Whatever their origin, the larger bodies may be conveniently called batholiths and the smaller ones stocks. They have specially significant meaning for the "granite" problem in general, because of the high reliefs of the belts, permitting observation to depths greater than those commonly possible in the peneplained Archean "granitic" shields. For these younger bodies field geology, as Read (1948, p. 2) emphasized, is of crucial importance, and his statement (p. 7) that accounting for them is "at the heart of the granite problem" is, with the qualifications already made, manifestly true. To illustrate the case a personal note is thought to be appropriate.

The present writer met the batholith-stock question squarely in his first serious undertaking in field geology, when, in 1892, he attacked the composite stock at Mount Ascutney, Vermont. There he found: (1) proof of significant feldspathization (incipient granitization) of the phyllites and other schists

surrounding the quartz syenite and granite of the mountain—this to a maximum distance of about 100 meters from the sharp contact with the syenite-granite; (2) also plain evidence that the syenite-granite replaced many cubic kilometers of the schists. The "room problem" was at once seen to be serious. He had already studied the writings of the French school, especially those of Michel Lévy, stressing metasomatism with resulting "granite." In 1897 he went to Paris to work under Lacroix, who has done so much to prove the reality of granitization, and the next year saw Sederholm demonstrating the same principle in the field. He also went to Heidelberg to improve his petrographical technique by study with Rosenbusch, who, while showing mastery of such technique, had exhibited little experience in field geology. Rosenbusch confessed to finding the intimate association of gabbro and alkali-rich syenite at Mount Ascutney to be a fact inexplicable according to his general philosophy of "eruptive" or "igneous" rocks. So that then and later, in discussions of alkaline rocks in general, the present writer showed that his student was not entirely docile under the "baleful" influence of the master. The student left Heidelberg, Paris, and Finland with no hint as to a practical answer to the "room problem" at Mount Ascutney. Its difficulty became still more impressive when he mapped in some detail nearly a score of batholiths and stocks distributed along the 600-kilometer Cordilleran section of the Canada-United States Forty-ninth Parallel boundary (Daly, 1912); this during six field sessions, from 1901 to 1906. It was in 1902, about ten years from his first bafflement at Mount Ascutney, that the student found the only promising solution —that of magmatic stoping, a principle which was independently deduced by Barrell (1907) at the Marysville batholith of Montana. After forty-six more years of steady concern over the room problem the writer has found, neither in the geological literature nor in his own additional field studies of big post-Cambrian "granite" bodies in Montana, California, New England, and the Pyrenees, any other reasonable solution. For these post-Cambrian masses replacement of the older rocks is obvious. For these masses all the arguments against the metasomatic origin of the Sial apply with special cogency. For them the emanational-one-way-street hypothesis is, as a matter of pure physics, incomparably harder to accept than

the hypothesis of replacement by "granitic" magma, along a two-way street, where stoping, remelting at some depth, and renewed differentiation are assumed.

Incidentally it may be recalled that not only all "metasomatists" but also nearly all the leading "magmatists," from Rosenbusch, Osann, Zirkel, and Teall, to Lacroix, Shand, and Bowen, have disregarded magmatic stoping as an essential process in the generation of the world's "granite," whether Archean (Sialic) or post-Cambrian.

Holmes (1945, pp. 91, 409), a convinced "metasomatist," has raised several objections to the stoping hypothesis. First he notes that with increase of depth xenoliths in "granite" "become gradually smaller and less numerous, and more and more like the granitic rocks enclosing them, until finally they disappear altogether. Evidently they have been incorporated in the granite and the space problem remains." But the "magmatist" has a different answer: the viscosity of his "granitic" magma at the upper levels of the cooling mass increases at maximum speed until the enclosing material attains the small strength sufficient to prevent further sinking, while lower down the liquidity persists much longer and thus permits complete cleansing of xenoliths.

Holmes's second objection reads: "Long 'islands' of country rocks like those of the metamorphic aureole can sometimes be recognized in the granite, their structures remaining in continuity with those of the bordering country rocks, though they may often be no more than vague shadowy outlines, seen through a veil of granitization. Black metamorphosed dolerite dykes, older than the batholith, can sometimes be traced into it as partly granitized 'ghosts.' Since the heavy dyke rocks did not sink, there is no reason to suppose that the associated metamorphosed sediments could have done so." A "magmatist" answer is that the "islands" are roof-pendants, stably supported in the "granitic" melt by their own strength, which with downward tapering of each pendant can be shown to ensure such stability until the whole batholith freezes solid.

The most serious objection is the third: "If granite magma ascends in great bulk towards the surface in this way, it should often have broken clean through the crust to form gigantic volcanoes erupting rhyolite and obsidian and the corresponding pyroclasts. But this has very rarely happened, as the re-

tention of the original roof clearly proves." This difficulty for the stoping hypothesis was fully apparent when the hypothesis was first proposed but the present writer has steadily believed the difficulty can be surmounted. A considerable number of cases are recorded where large bodies of rhyolite, dacite, and obsidian have been erupted in areas where masses of apparently syngenetic "granites" were developed. A remarkable example, recently described by P. Lapadu-Hargues (1947, p. 950), is in the Eglab massif of the western Sahara, where at intervals for 150 to 200 kilometers a huge granite batholith passes continuously upward into broad cappings of rhyolite. It is, of course, conceivable that in many other mountain belts where erosion was prolonged similar rhyolitic cappings were completely destroyed. Nevertheless, it is probable that in perhaps most instances "granitic" batholiths did not break through to the earth's surface. A leading reason for this may well have been the freezing of the magma, chilled by the stoping itself as well as by conduction of the magmatic heat into rock which the stoping magma found to be cooler and cooler as it made its way upward. Perhaps, too, progressive loss of gas and corresponding rise of the freezing temperature is to be considered. On various grounds, therefore, the writer does not regard Holmes's third objection as compelling.

His fourth reads: "If granite magma rose from the depths in quantities corresponding to the enormous volumes of batholiths, it would be by far the most abundant of all magmas. In this case rhyolite should be the most abundant of all volcanic rocks. But it is not." For the "magmatist" "granite" is actually by far the most abundant of the massive rocks in the orogenic belts, the regions now under discussion. We have just found good grounds for doubting the added remark about rhyolite in these same belts.

Holmes (1945, p. 409) is willing to entertain the idea that convection to great depth in the earth may be competent to cause mountain-building of the Cordilleran type. This action, if real, must have resulted from the exceedingly small potential due to relatively small difference of temperature in the thick earth-shell involved. Yet he is averse to crediting the reality of solid-liquid convection to much smaller depth, though the potential is here incomparably greater and the overturn of material incomparably smaller in quantity. One must con-

clude, therefore, that Holmes in his general review of physical geology should not have had a priori objection to stoping by acid magma to the depth of ten or twenty kilometers. Since more thoroughly than any other geologist he has expressed doubts about the efficiency of magmatic stoping, analysis of arguments against the hypothesis seems not to invalidate it as easing explanation of post-Cambrian batholiths and stocks.

For those bodies the difficulties of the "metasomatists" include some of those already listed when the origin of the Sial was considered, but some of the arguments proffered by members of the school deserve special attention. But beforehand a statement by Bowen (1948, p. 88) at the Ottawa symposium may be recalled: "Though, locally, volume for volume replacement of individual beds may be demonstrated, the claim that wet granitization offers a solution of the 'room problem' is altogether spurious. Material pushed up chemically occupies just as much room as the same material pushed up mechanically. Even though repeated equivolume replacement is postulated, it cannot be repeated *ad infinitum*. There would necessarily be a large net addition of material in the upper crust. Wet granitization does not solve, it merely evades the room problem. The magmatist has, however, found not unreasonable real solutions of the problem."

In whatever way the "metasomatists" account for the earth's "granitic layer," they must admit that, according to their own views, the bulk of each post-Cambrian batholith of "granite" was itself metasomatized Archean (Sialic) "granite" and its own derived sedimentary products. Would "emanations" develop in the post-Cambrian orogenic belts "batholithic" rock-types like those of the primitive earth-shell, which, unless all signs fail, is best represented in visible presence by the oldest Archean terranes? The fact is that, apart from the problematical charnockite and the equally mysterious gneissic structure of these oldest "granites," dominant rock types of the Archean match well with the dominant types in the post-Cambrian batholiths and stocks.

Another trouble for the "metasomatists" in their explanation of these bodies is their comparative homogeneity in the vertical direction, a characteristic often displayed also over outcrop areas measurable in hundreds of square kilometers. An example is the batholith crossed by the Similkameen River

of Washington State and British Columbia (Daly, 1912, p. 435). There the mass extends from the highest point in the valley wall down to the river nearly 2000 meters lower down. No floor is to be seen anywhere and the body has lost by erosion an unknown amount of substance above its highest outcrop. Many other batholiths of Alaska, British Columbia, and California afford proof of great thickness and total volume as well as comparative homogeneity, and there can be little doubt that these regions fairly represent the grandeur of the batholithic development along the cordilleran chain stretching from northern Alaska to Cape Horn—the world's most spectacular display of post-Cambrian "granite."

The almost perfect homogeneity of many batholiths to visible depths is by the "metasomatic" doctrine hard to understand not only because of the pronounced heterogeneity of the invaded rocks but also because of the strong probability that, if the emanations were fluids, made "thin" by the presence of much water, one would expect the upper part of each batholith to be specially rich in minerals stable in the presence of much water. Yet there is no field evidence of such differential hydration in the post-Cambrian bodies.

Further, no protagonist of the doctrine has shown why those bodies are confined to orogenic belts or, as already observed, why diffusion could have accomplished the enormous molecular replacement in the limited duration of an orogenic revolution.

Those who emphasize upward diffusion of emanations from great depth cannot doubt that magmatic basalt has risen along each belt both before and after the paroxysm of mountain-building and nevertheless retained the same composition. Yet by the metasomatic hypothesis the basalt itself should have been chemically changed while deep-sourced emanations were passing through it to the high batholithic levels.

Again, the observer exploring the high cliffs of the Cordillera sees that the lateral, steeply inclined contacts of the "granitic" giants as well as the contacts of enclosed xenoliths are commonly if not generally sharp. He notes there the relative slightness of metasomatism. He discovers the never-failing fringe of apophysal dikes from batholith and stock. He may think of the old masters. Will he find more comfort in the vaguely defined "plutonism" of Lyell than in Hutton's exciting demonstration of magmatic granite?

That some metasomatism has accompanied or immediately followed the emplacement of Cordilleran batholiths is clear, but their most experienced students have no doubt as to which is the horse and which the cart. They have found that such molecular replacement is much more conspicuous at the roof of a batholith than along its lateral contacts. The most remarkable example, quantitatively considered, is that reported by G. H. Anderson (1937). After prolonged exploration he explained the "Pellisier granite" of the California Inyo Range as the product of metasomatism of Cambrian and Pre-Cambrian schists by emanations from beneath. If he is right, he has found the largest Cordillera body proved to have been developed by metasomatism. He pictures it as a roof phenomenon. The Pellisier "granite" rests on the Boundary Peak granite, which in the molten, batholithic state gave forth the replacing fluids. From his cross-section one sees that Anderson assigned the remarkable thickness of 600 meters to 900 meters to the "Pellisier granite" while the parent Boundary Peak granite is two or three times thicker, even though no bottom for it appears in the draughted section. He too had no doubt as to which was the hen and which the egg. Like Sederholm and Michel Lévy he felt no need of seeking in mystical depths the immediate source of the working fluid.

CONCLUSION

To summarize: it seems evident that "metasomatists" have left gaps of critical importance in every published version of their hypothesis. They should make more specific: (1) their ideas concerning the nature of the Sial and its mode and time of development; (2) their premises with respect to the state, composition, source, energy, and mode of travel of the assumed emanations; (3) their estimates of the volumes of magmatic "granite" formed by melting of mountain roots, and their estimates of the volumes of "granite" made molten by anatexis; (4) their explanation of the fact that during at least half a billion years no discernible granitization of the earth's crust has been registered under the vast, deep Pacific or within nearly all of the extensive Canadian "shield"; (5) the rôle of crystal-fractionation plus remelt-fractionation in petrogenesis; (6) truly compelling grounds for doubting large-scale magmatic stoping, whether in relation to the

earth's "granitic layer" as a whole or in relation to batholiths and stocks of the mountain chains; (7) explanation of the absence of material in the visible part of the earth's crust, corresponding to the "basic fronts" expected by the hypothesis; (8) the meaning of the almost perfect chemical uniformity of basaltic magma erupted since a comparatively early stage of the Archean; (9) the volume and composition of the ocean in relation to the hypothesis; (10) the commonly displayed sharpness of contact of post-Cambrian batholith or stock with the respective invaded formations; (11) the nearly perfect chemical and mineralogical uniformity of so many of these subjacent masses in the vertical direction; and (12) the restriction of typical post-Cambrian bodies of the sort to the mountain chains.

Until all the twelve kinds of argumentative trouble are overcome the "metasomatists" cannot be said to have succeeded in their effort to account for most of the world's "granite". As briefly indicated in the body of the foregoing text, there seems to be a more excellent way, though it too has to be speculative and reach back into the mists of cosmogonic theory.

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UNUSUAL STYLOLITES*

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ABSTRACT. Stylolite seams occurring at near right angles to bedding planes are found in certain limestones along the eastern flank of the Front Range and Wet Mountains of Colorado, where known thrust faults exist.

Limestones of the Pennsylvanian Fountain, Jurassic Morrison, and Cretaceous Greenhorn and Niobrara (Timpas) formations were studied in detail. The stylolite seams intersect bedding planes at remarkably constant angles whether they occur in undeformed, normally dipping, or strongly over-turned strata. The seams are only roughly parallel to each other, but the axes of the columns show almost no variation in attitude within an exposure.

It is believed that the stylolites formed during the early stages of Laramide orogeny. A system of transverse joints developed in the relatively undisturbed beds of the section and solution along these joints, combined with continuing stress associated with the thrusting produced the stylolites. The major deformation of the beds, including local over-turning, is later than the stylolites.

INTRODUCTION

Because of recent discussion regarding the origin of stylolites; Goldman (1940), Shaub (1939), Stockdale (1943) and others; the nature and occurrence of these structures in certain limestones near Colorado Springs, Colorado, is believed to be significant. The evidence, besides firmly establishing the mode of origin, suggests two possible uses of stylolites in the interpretation of structural problems.

The area of detailed study extends from the Colorado Springs region southwest along the east flank of the Colorado Front Range, across the Canon City Embayment to the east flank of the Wet Mountains. The sedimentary formations on the eastern slopes of the mountains have been deformed and show dips ranging from a few degrees to vertical, with overturning at some localities along both mountain fronts. The formations dip gently to the southeast in the Canon City Embayment, but are almost horizontal in the center of the embayment at Portland, Colorado.

The stylolites are found in limestones of the Pennsylvanian Fountain formation, the Jurassic Morrison formation, and the Cretaceous Greenhorn and Niobrara (Timpas) formations. They are most numerous, best developed, and best exposed in the Timpas member of the Niobrara formation. Stylolites of each formation will be discussed separately.

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MODE OF OCCURRENCE

PENNSYLVANIAN FOUNTAIN FORMATION

Lithology: Limestones, which comprise a very small part of the Fountain, occur in the upper one hundred feet of the formation. The limestone is gray to reddish-gray, dense, commonly laminated, and exhibits good conchoidal fracture. It occurs in discontinuous beds or lenses which are locally nodular. Irregular white crystalline calcite masses, averaging one quarter inch in diameter, commonly occur in the rock. Wavy laminae of poorly indurated red shale one-eighth inch thick are interbedded with the limestone.

The lithology of the Fountain is extremely complex and individual beds can be traced for only short distances.

Stylolites: Stylolites were observed in the vertical and slightly over-turned beds of Fountain limestone in the low saddle south of Keeton's ranch house on Little Fountain Creek.* The seams are generally parallel to each other and intersect bedding planes at angles of about eighty degrees. The individual stylolite columns are cone-shaped and were observed to have a maximum height of three quarters of an inch, the average being one quarter inch.

At a road cut in Deadman Canyon, stylolites were observed in gently dipping beds of limestone. Some seams cut the bedding planes at steep angles. Other seams, anastomosing considerably, occur parallel to the stratification, but the two sets were not observed to cross. Of the seams parallel to bedding planes, many are unquestionably stylolites, yet some of the same seams appear only as wavy shale partings when traced several inches. The thickness of the shaly material in these undulations is several millimeters, but in the stylolitic portions along the same plane it is only about two-tenths of a millimeter. Since a greater thickess of shaly material occurs in the wavy partings, there appears little possibility that the undulations are embryonic or poorly developed stylolites. Probably these lenticular shale seams are depositional, the thinner edges of the seam being secondarily developed into stylolites, whereas the thicker

* Most of the specific localities mentioned in this paper may be found on the Colorado Springs Quadrangle map or on the new maps, now in press, of the Cheyenne Mountain, Big Chief Mountain, Lytle, and Mount Pittsburg Quadrangles which cover the southwestern quarter of the old quadrangle.

portions of shale prevented the interpenetration of the limestone to form stylolites.

Of the transverse stylolites observed in the Fountain, all intersect bedding planes at steep angles whether the beds be over-turned or dipping only slightly.

JURASSIC MORRISON FORMATION

Lithology: Limestone, especially gray, lithographic or sublithographic type comprises a minor part of the Morrison and occurs about sixty feet above the base of the formation. The beds are from two to twenty-four inches thick and locally there is fine lamination.

Although the lithology of the Morrison is extremely variable within the area, the limestone beds are persistent and of essentially uniform lithology.

Stylolites: Stylolites are not particularly common in the Morrison. The best locality is at a small, abandoned tunnel one hundred yards east of Colorado Highway 115 near the large road-cut at the south end of Deadman Canyon.

The stylolite seams are transverse, intersecting the bedding planes at about eighty degrees. The stylolite columns are conical and have a maximum height of three-quarters inch and an average of one-quarter inch.

CRETACEOUS GREENHORN FORMATION

Lithology: The Greenhorn consists of limestone beds from three to eighteen inches thick separated by shale beds from six to forty-eight inches thick. The limestone is a dense, gray, argillaceous rock with good conchoidal fracture. The shale is light gray, poorly indurated, and calcareous. Thin bentonite beds occur locally in the shales, and veins of gypsum, generally less than a quarter of an inch thick, are common. The lithology of the Greenhorn is uniform throughout the area and the dominance of shale in the section makes good exposures of the limestone beds rare.

Stylolites: Although only a few stylolites were observed in the Greenhorn, they are all of the transverse variety. The seams are roughly parallel and intersect bedding planes at angles of about seventy-five degrees. The nature and occurrence of known stylolites in the Greenhorn are similar in every

respect to the transverse stylolites of the other formations studied.

CRETACEOUS NIOBRARA (TIMPAS) FORMATION

Lithology: The lower part of the Timpas consists of limestone beds from three to twenty-four inches thick separated by shale beds from one-half to ten inches thick. It is in this portion that the stylolites are best developed.

The limestone is a gray to bluish-gray, dense, argillaceous rock with good conchoidal fracture and containing numerous *Inoceramus deformis* shells and shell fragments. Iron sulfide concretions are common. The shales are light to medium gray, poorly indurated and calcareous. Lamination is generally present but is best developed along contacts between shale and limestone, which appear to be gradational.

The lithology of the Timpas is remarkably constant throughout the area.

Stylolites: Stylolites may be observed in almost any good exposure of the lower Timpas, but one of the best and most accessible localities is an abandoned roadside quarry on Colorado Highway 115 just south of Little Fountain Creek.

TABLE I

Attitude Relationships of Beds and Stylolite Seams

Formation & Age	Dip & Strike of Stratum	Dip & Strike of Seam	Approx. Angle of Intersection
Niobrara (Timpas) U. Cret.	N14W 30N	N56E 73N	87 degrees
	N15W 24N	N50E 69N	82 "
	N25W 27N	N48E 76N	84 "
	N11W 25N	N42E 62N	80 "
	N28W 23N	N33E 47N	62 "
	N 7W 32N	N52E 68N	87 "
	N23W 34N	N29E 71N	86 "
	N22W 26N	N35E 57N	73 "
	N14W 20N	N58E 79N	86 "
	N10W 24N	N44E 57N	67 "
	N 5W 7N	N51E 80N	83 "
	N 8W 8N	N33E 64N	71 "
	N20W 11N	N41E 70N	78 "
	N 2W 11N	N23E 73N	81 "
	N12W 8N	N40E 70N	74 "
Greenhorn U. Cret.	N12W 30N	N28E 52N	75 "
Morrison Jurassic	N10W 24N	N74E 80N	83 "
Fountain Penn.	N50E 57N -overturned	N45E 28S	80 "

The stylolite seams are distinctly transverse to the bedding of the limestone. Except for minor irregularities and branching, the seams are roughly parallel to each other in the ex-

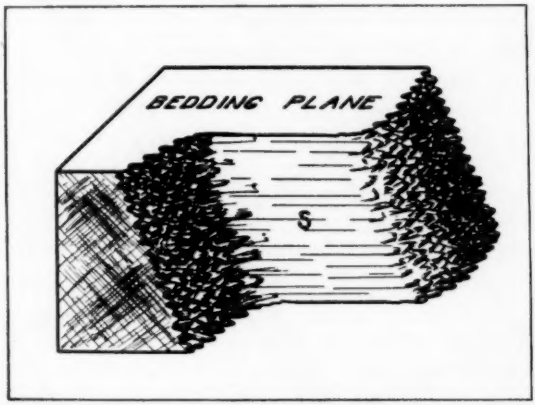

Figure 1. Stylolite seam offset along slickensided plane (s) which is parallel to cone-axes of the stylolite.

posure. The planes of the seams intersect the bedding planes at angles averaging about eighty degrees (Table I, figs. 1, 2).

Almost all of the stylolites are of the angular type with individual penetrating elements being cone-shaped. The individual cones are not necessarily oriented normal to the plane of the seam, but may be inclined at any angle up to ninety degrees, depending upon variations in the strike of the seam. In any case, the axes of the cones are parallel throughout any exposure. Some of the seams were noted gradually to change strike almost ninety degrees within a distance of several feet, and then similarly to change back to the original direction several feet farther away. The stylolite cones are inclined steeply where the seam trends in the usual direction, but where the seam gradually changes strike, the cones meet the seam at shallower angles until, at the greatest deviation of the seam, the cones lose their identity and ordinary slickensides appear. Crystalline calcite surfaces one-quarter inch thick comprise the slickensided portions of the seam. Where the normal trend of the seam is resumed, stylolites once again appear. The slickensides have an alignment identical to the attitude of the cone axes (fig. 1).

The observed height of the columns varies from minute to a maximum of four inches, the average height being about a quarter of an inch. The largest stylolites are of the columnar

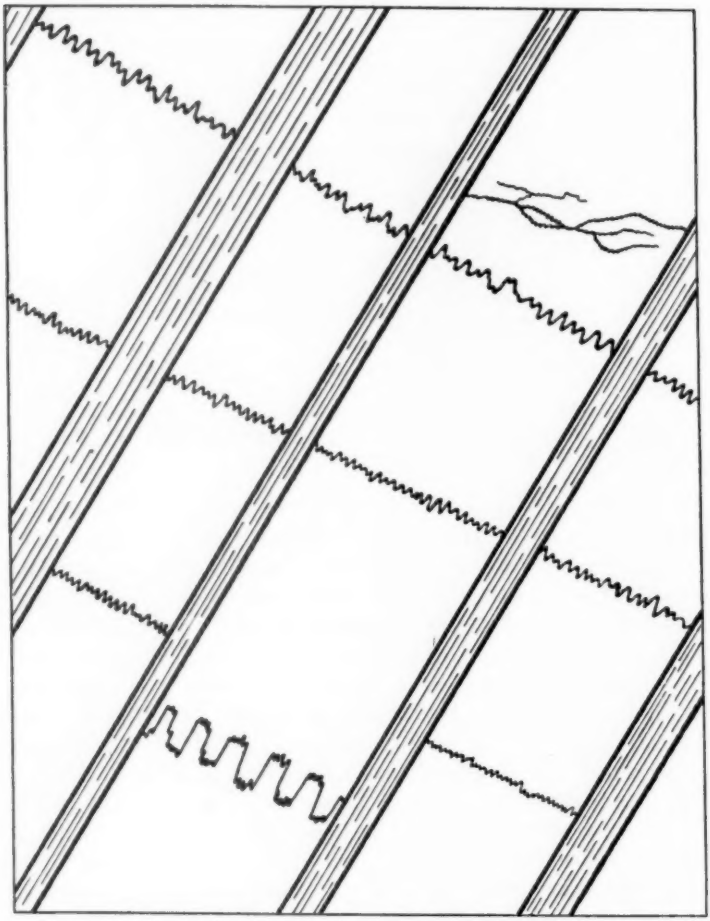

Figure 2. Composite diagram showing typical relationships of stylolite seams to limestone beds, white; and shale beds, shaded; in Niobrara (Timpas) formation.

type, having columns about two inches wide. The extremities of these stylolites consist of numerous small cones identical to those forming the smaller stylolites. Perhaps the columnar

type is a characteristic of only the larger, more completely developed stylolites, the conical type being limited to the smaller ones.

The transverse seams may or may not be restricted to a single limestone stratum. Stylolites with low amplitudes were observed to disappear when traced into ten-inch shale beds, only to reappear in numerous succeeding limestone strata, the attitude of the seams remaining constant throughout. However, some of the stylolites having greatest amplitudes are restricted to a single limestone stratum with no trace of the seam appearing in adjacent shales or limestones, although the shale parting may be a fraction of an inch thick. Therefore the persistence of a seam bears no relationship to the size of the stylolites or to the thickness of the shale beds which separate the limestone strata.

Stylolites were observed parallel to bedding planes, but the occurrence of these is rare. This type is found in limestone beds of the lower Timpas only within about two inches of the bedding planes, where lamination is common. Transverse stylolites were noted to cross the other set. At the intersection, there appears a discordance on the parallel type seam which indicates the transverse seams to be younger.

A false impression of the seam attitudes results if the stylolites are observed only in cross section. The true seam attitude can be determined best by observing the weathered surfaces of the limestone where the planes of the seams are exposed completely. The erroneous impression of attitude is well exemplified by the larger stylolites having amplitudes of several inches. If the limestone is fractured across the seam at a very low angle, haphazard stylolites appear in cross section because of the decapitation of the columns. This also gives the false impression that a number of erratic seams are present, whereas only one large, rather uniform seam occurs, which is related in attitude to the other true seams.

AREAL DISTRIBUTION

Within the area of study, stylolites are most numerous and best developed along the flanks of the Front Range and Wet Mountains, especially where known thrust faults exist. The Cheyenne Mountain thrust marks the steep eastern face of the Front Range from Colorado Springs to the vicinity of

Little Fountain Creek. In most places where the Timpas crops out within these limits, transverse stylolites are very abundant. Beyond the mappable trace of the fault to the southwest, and at exposures in the Canon City Embayment, only a few transverse stylolites were observed, these having amplitudes of less than one-eighth inch. Southwest of Canon City, Colorado, on the west side of the embayment, the sedimentary beds are deformed by the Wet Mountain thrust, and show normal dips to the east, but are over-turned locally. Numerous well developed transverse stylolites were observed in limestone beds dipping about forty degrees to the east. The relationships of the seams and beds are comparable to those already discussed.

ORIGIN

Beyond doubt, these structures are stylolites in spite of the transverse mode of occurrence. By studying a hand specimen containing the structures, any observer would identify them as stylolites. The transverse attitude, therefore, cannot be used as a criterion to eliminate them as stylolites.

The main principles of Shaub's "contraction-pressure" theory of primary origin of stylolites will be briefly discussed. Shaub (1939) states that impermeable clay seams trap upward moving pore water in limestone oozes underlying the clay. The upper part of the ooze becomes more plastic than the lower part as water accumulates. A slow drying of the ooze results in stress differences and places of low pressure. The ooze, under the force of gravity or other pressures, flows into the low pressure areas shearing the clay band, the result being a stylolite seam.

Shaub's theory provides no adequate explanation for stylolites transverse to normal bedding. The occurrence of this type, on the other hand, contradicts Shaub's main principles. Clay partings along transverse stylolites could not have been originally deposited as clay seams. Even if this were possible, upward moving pore water would not accumulate under clay seams dipping eighty degrees.

Furthermore, the occurrence of transverse stylolites with remarkable constant characteristics in formations ranging in age from Pennsylvanian to Upper Cretaceous precludes any possibility of a primary origin. Because stylolite seams of all formations studied intersect bedding planes at angles remark-

ably alike, it is inconceivable that the stylolites of each formation could have formed successively as each formation was deposited.

The most reasonable conclusion is that after the deposition of the Cretaceous beds, the relatively undisturbed beds were jointed by the early movements of the Laramide Revolution. Solution activity along the transverse joints, under the influence of continued stress associated with thrusting, caused the development of stylolites simultaneously in the limestones of various formations. Beyond the influence of thrusting, especially in the Canon City Embayment where the beds are essentially horizontal, stylolites are lacking. Following the stylolite development, the major thrusting deformed the strata and caused local over-turning.

The largest and best developed stylolites usually conform to the general alignment, but the smaller ones are irregular, commonly branching and anastomosing. The former correspond to the best original joint development, the latter to smaller and more irregular joints and fractures, which are common in dense limestones.

The stylolite columns are always oriented perpendicular to the direction of pressure, which must have been constant over wide areas. Because of irregularities in the original joints, individual seams have varying strikes. Therefore the columns, although mutually parallel within an exposure, meet the seams at varying angles of inclination. Where a stylolite seam is inclined to the direction of pressure, the adjacent limestone blocks could not slide past each other, but rather had to interpenetrate as the limestone was removed by solution along the joints. But where the joint is essentially parallel to the direction of pressure, the adjacent blocks easily slid past each other forming slickensides.

It is generally agreed that slickensides may be produced by small displacements of the rocks along a fracture. The slickensides on fractures parallel to the stylolite columns were produced by movement not exceeding that involved in the making of the stylolite. With stylolites averaging less than half an inch in amplitude and having very thin residual clay seams the movement was certainly small yet excellent slickensides were developed.

The association of stylolites and slickensides proves beyond

doubt the importance of pressure in the formation of stylolites, since the slickensides are genetically dependent upon pressures to cause relative movement of the adjacent blocks. The results of Stockdale's work (1943) show that solutions dissolve rock material most easily at points of greatest pressure. The greatest pressure along a joint would be in the portion which is most nearly perpendicular to the pressure direction, and the points of lowest pressure would be where the joints are parallel to the pressure direction. Therefore it is conceivable that calcium carbonate was dissolved at the higher pressure portion of the original joints where stylolites formed, and that it was redeposited in the low pressure portion, being slickensided by the relative movement of the blocks, or inheriting the slickensides from the adjacent limestones.

The persistence of a stylolite seam depends on the extent of the original joint. The angle at which the stylolite seams intersect the bedding planes is that of a system of joints common to all the formations studied within the area.

It is evident that the only theory providing adequate principles regarding the origin of these transverse stylolites is the "solution-pressure" theory of secondary origin of stylolites as presented by Stockdale. In this area the pressure was orogenic rather than static as is the case in better known areas of stylolites.

PROPOSED USES

The study of transverse stylolites may be of structural significance in two ways:

1. To determine the direction of regional stresses.
2. To determine top and bottom of beds and therefore the structural attitude of isolated outcrops.

Direction of regional stresses: Because most, if not all, stylolites are developed by combined solution and pressure the cone axes will be parallel to the pressure direction. For transverse stylolite seams the cone axes will indicate the direction of regional stresses whereas stylolite seams parallel to the bedding indicate the stress of load.

Determination of top and bottom of beds: The present opinion regarding the significance of stylolites in determining top and bottom is best stated by Shrock (1948, p. 240):

"There seems to have been no mention of any character-

istic of stylolites which might make them useful in determining the top or bottom of a sequence in which they occur."

Under circumstances similar to those in the area studied it may be possible to use stylolites as a key to structural relationships. Here it is possible to study the stylolites in numerous exposures where top and bottom of beds and structural attitude can be determined with certainty by various criteria. These studies show that:

1. The attitude of the stylolite seams with respect to the bedding planes is approximately constant without regard to age of the limestones or structural attitude.
2. The attitude of the stylolite cones has an even more constant relationship to the plane of the bedding than does the attitude of the stylolite seams, and that the cones are inclined rather than normal to the seam.
3. The stylolites developed by solution and pressure along joints in the limestone before the major deformation, including local over-turning, occurred.
4. The strike of the stylolite seams is appreciably different than the strike of the beds.

If, in such an area, there are isolated exposures of stylolitic limestones in which top and bottom of the beds and therefore the true structural attitude cannot be determined by other criteria the stylolites may provide an adequate criterion.

The limiting directions and angles of plunge of the stylolite cones can be determined by means of a simple model consisting

TABLE II

Attitude Relationships of Cone Axes in Beds Known To Be Dipping Normally

Formation	Attitude of Bed	Directions and Plunge of Cone Axes
Niobrara (Timpas)	N 8W 26N	S69E 16
	N 6W 26N	S64E 17
	N 5W 30N	S66E 22
	N10W 28N	S62E 21
	N 4W 29N	S66E 21
	N 3W 27N	S63E 19
	N 6W 29N	S66E 20
	N 2W 30N	S63E 16
	N16W 10N	S65E 10
	N15W 8N	S70E 10
Morrison	N10W 24N	S70E 20

TABLE III

Attitude Relationships of Cone Axes in Beds Known To Be Overturned

Formation	Attitude of Bed	Directions and Plunge of Cone Axes
Niobrara (Timpas)	N 8W 54S	S25W 25
	N 2E 59N	S25W 30
	N10W 47S	S33W 30
	N20E 45N	S20W 25
Fountain	N30E 75N	S40W 5

of a cardboard box and a pencil. The box is used to represent the bed and is placed in measured attitude. The pencil is inserted at the measured direction and plunge of cone axes. The box is then rotated normal to its strike and the possible directions of plunge of the stylolite cones are noted for cone axes in beds not over-turned. Continued rotation of the box will demonstrate the cone attitudes in over-turned beds. Because the cone axes are nearly parallel to bedding planes, the direction of plunge will change at the first over-turning. Thus, over-turned beds could be recognized by a plunge direction of cone axes which could not possibly exist in beds of a normal depositional sequence (Tables II and III).

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SPHEROIDAL STRUCTURES IN ARIZONA VOLCANICS

JOHN H. FETH AND JOHN W. ANTHONY

ABSTRACT. Spheroidal forms occurring in a red welded keratophyre tuff and in a devitrified gray tuff in the Canelo Hills, southeastern Arizona, are described.

The keratophyre tuff has been traced for approximately one mile. Thickness ranges from 20 to 25 feet. The spheroids range from a fraction of an inch to 12 inches in diameter, and constitute from 50 to 75 percent of the weathered surface throughout its entire extent. Flow structure, apparently continuous through both matrix and spheroids, is clearly displayed.

The spheroids in the gray tuff have been found in an area measuring about 600 by 200 yards, and occur about 100 feet lower in the volcanic sequence than the welded tuff. They are less abundant and less prominent on the outcrop than the spheroids in the welded keratophyre tuff, but occur in many places free from matrix in the talus. All have cores, most of which are tesselated calcite.

Thin sections were prepared to encompass entire equatorial cross-sections of individual spheroids.

Under the microscope sporadic spherulites were found within the larger spheroids in the welded tuff. Well developed flow structure is characteristic. Both primary and secondary quartz are abundant. An indication of radial orientation of quartz and feldspar grains suggests that the growth of the spheroids was determined by a primary control. Absence of demonstrable secondary control points toward the same conclusion.

The gray tuff shows heavy concentrations of secondary calcite other than that in the cores, impartially distributed in matrix and spheroids.

Comparable structures in volcanic rocks from other Arizona localities are mentioned.

THE occurrence of spheroidal structures in profusion in a red keratophyre tuff and the presence of comparable nodules in an adjacent gray tuff engaged the attention of the senior author during field mapping in the northern Canelo Hills, Santa Cruz County, Arizona. The Canelo Hills lie sixty road miles southeast of Tucson and twenty-five miles east and north of Nogales. They form a connecting link of high land between the Huachuca Mountains to the east and the Santa Rita Mountains to the west.

The series of volcanic rocks in the area includes rhyolites, andesites, and tuffs, and has a thickness of 991 feet on Mount Hughes, two miles distant from the locality where the spheroidal structures are most plentiful. Schrader (1915, pp. 70-75) considers the volcanic series to be Tertiary in age. No more recent data concerning their age has been published as far as is known.

The volcanic rocks were extruded over an eroded surface of Cretaceous (?) sediments, and have been gently warped in the northern Canelo Hills into a broad anticline whose axis trends northwest-southeast. These volcanic rocks are covered in part by a deeply eroded block of Permian sediments, principally limestones, overthurst upon the area, and in part by a fanglomerate composed of cobbles and pebbles of Permian limestone and of the volcanic materials. The rocks in the area are cut by high-angle faults, one set trending approximately north-south and a second approximately east-west.

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FIELD OCCURRENCE

Spheroids occur in a dark red keratophyre tuff 20 to 25 feet thick. They range in diameter from a fraction of an inch to about 12 inches, and weather out on the surface of the tuff, to form a nodular structure of striking appearance (pl. 1, fig. 1). As much as 75 percent of the outcrop is covered by the nodules in localities where the rock stands out from a slope, as on low cliffs. Elsewhere the spheroids thickly litter hilltops with rounded masses. The outcrop extends for more than a mile without noticeable diminution in the quantity of spheroids. The outcrop is terminated at the southwest by a high-angle fault. There the tuff is in contact with the Cretaceous (?) series which is exposed in a canyon where the overthrust Permian limestones cap the opposite canyon wall. To the northeast the tuff is cut off by a high-angle fault.

It is noteworthy that flow lines in the keratophyre tuff are continuous through matrix and spheroids alike, but that the spheroids are separated from the matrix by a sharp line of demarcation. The spheroids weather out from the matrix, leaving clearly defined hemispheric cavities on the outcrop. On weathered surfaces many of the spheroids exhibit a warty character analogous to the "cauliflower-like habit" mentioned

Fig. 1. Outcrop of welded keratophyre tuff showing profuse development of spheroidal structures. Horizontal projections on staff 12 inches apart.

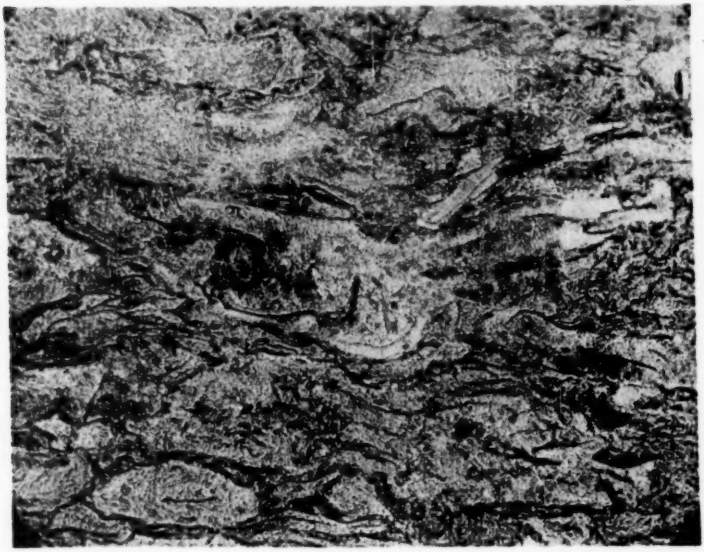

Fig. 2. Flow structure in welded keratophyre tuff. Specimen of matrix. Ordinary light. (X 60).

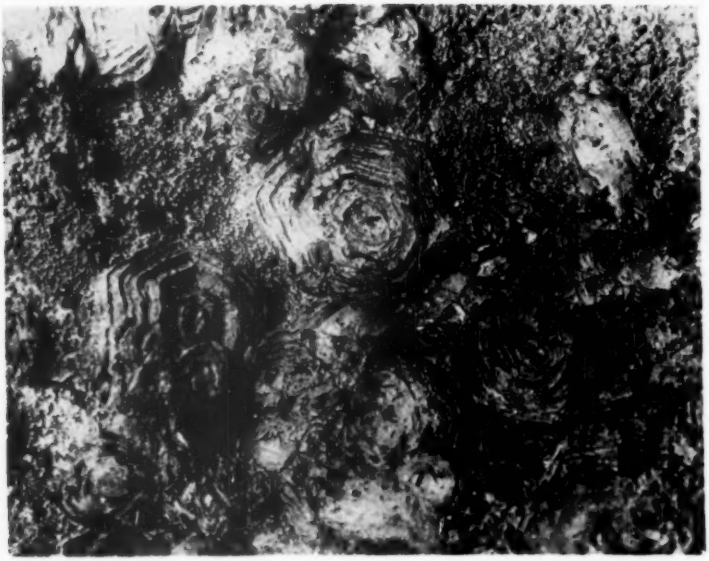

Fig. 1. Zoned quartz crystals developed in vug in welded tuff spheroid. Maximum diameter of individual crystals is about ½ inch.

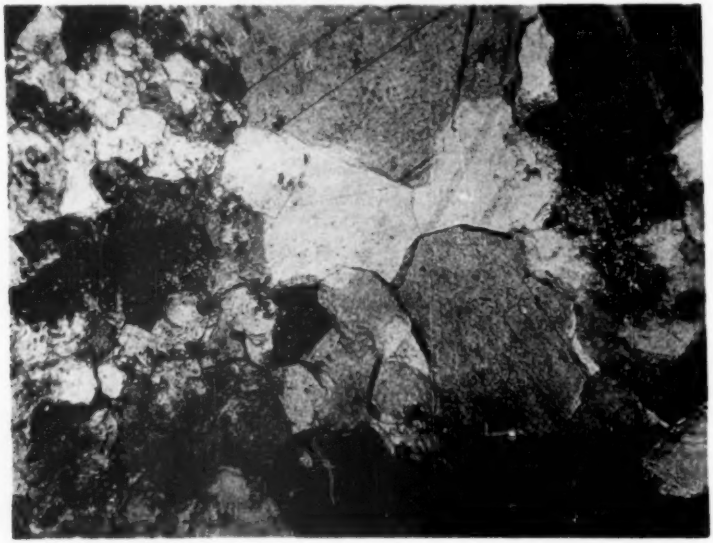

Fig. 2. Tesselated calcite occurring in typical core of gray tuff spheroid. Crossed Nicols. (X 60).

by Ross (1942, p. 192) in connection with Oregon "thunder eggs." In other features of origin and internal structure, there appears to be little similarity between the two.

In none of the dozens of red spheroids cracked open was any megascopically visible core discovered. Nor is there any indication of radial structure in hand specimens. Weak color banding is displayed in a small percentage of the nodules.

Local concentrations of nodules having prominently developed concentric shell structure appear in limited areas along the outcrop. These nodules show a solid central mass, surrounded by a partial outer layer from ¼ to ½ inch thick, separated from the central mass by an open space usually in the order of ¼ inch thick. One-fourth to one-half of the core of the spheroid may be covered by this partial shell. Silica is commonly present in the vugs so formed. It occurs as mammillary deposits and as euhedral crystals of quartz projecting from both walls of the void, or, in some specimens, as crystals showing as many as ten concentric zones of growth (pl. 2, fig. 1). Some crystals are oriented with the *C* axis parallel to the wall of the cavity, but more crystals have the *C* axis normal to the wall. In the latter case, the zoned crystals show asymmetric growth, the greater development in about 75 percent of the specimens noted being toward a common locus on the circumference of the hemisphere which is the cavity wall. Each period of quartz deposition in the zoned crystals is marked by a distinct ridge separated from its neighboring ridge (in the same crystal) by a valley. The structure suggests alternate waves of deposition of quartz and some other mineral (calcite?) and subsequent removal of the other mineral, leaving the ridge-and-valley structure. The larger zoned crystals are as much as one-half inch in diameter and contain as many as ten distinct zonal ridges.

Other vugs contain deposits of powdery, black manganese dioxide, or of a very fine, white, powdery mineral which may be a zeolite. Rarely, all three minerals occur in a single vug.

In a ten-foot zone stratigraphically just below the spheroidal keratophyre tuff, almond-shaped vugs are abundant. These cavities range from one-half inch to six inches in length, and their height is approximately one-third the length. Some are empty; others are lined with any or all of the same minerals—quartz, manganese dioxide, or zeolite (?) — mentioned above.

Arrangement of filled or empty cavities appears entirely haphazard. It is not clear whether this zone is confined to a flow distinct from that in which spheroidal structures are well developed, or whether it is in the lower portion of the same flow. The almond-shaped vugs, however, are present, although in smaller number, in the zone of spheroidal development. Some serve as centers around which spheroids develop; but these spheroids tend to be weakly formed and rarely weather out of the matrix. This is in marked contrast to spheroids formed without determinable centers which weather out without loss of form.

A poorly defined joint system cuts across the keratophyre tuff, affecting both spheroids and matrix. No displacement was observed along these parallel breaks.

The area in which spheroids have been found in the gray tuffs is much smaller than that within the red. Spheroids in the gray tuff have been found only in one locality, a valley underlying a bluff formed by the keratophyre tuff. The area measures about 600 x 200 yards.

In hand specimen the tuff is light gray, fine-grained, and gritty. Prominent in the gray matrix are abundant xenoliths of red and purple volcanics, gray quartzite, and red shale. Shiny irregular flakes of a golden mica, probably altered biotite, are plentiful. Bleached zones adjacent to joints are prominent. Three sets of joints at right angles divide the rock mass into blocks, the edges of which are rounded by weathering. The effect, viewed from a little distance, is that of a pillow lava. Closer inspection reveals joint control.

Spheroids in the gray tuff are characterized by their relatively small size, one-fourth to three inches in diameter, by their hardness which exceeds that of the matrix, and by their irregular boundaries. The spheroids occur loose on the surface of the gray tuff and accumulate on small talus slopes below cliffs carved by gullying of the tuff. Most of them are not visible on the outcrop except where rimmed either by a zone of bleaching or by a zone of weak red stain. Comparable circular bleached areas, some of them rimmed by red stain, occur sparsely on the outcrop with no apparent associated spheroidal development.

Eighty percent of the spheroids examined have a calcareous core. The calcite is colorless, white, or rarely, gray, red, or

black. In the remaining 20 percent of the spheroids, the cores consist of rounded fragments of quartz, quartzite, or sandstone. In none of the gray spheroids is a core completely missing.

The mode of occurrence suggests that the spheroidal masses are controlled by concentration of a cementing substance about a xenolithic nucleus. The assumption may be made that where tessellated calcite forms a core it represents a recrystallized fragment of limestone deposited contemporaneously with the tuff.

An objection to this interpretation is the abundance of xenoliths of shale, volcanic fragments, and limestone throughout the tuff, unaccompanied by the development of spheroidal forms. Another objection is local concentration of calcite grains in both tuffaceous matrix and spheroids.

Geological literature, insofar as can be determined, contains few pertinent descriptions of spheroidal masses in volcanic rocks. Structures that appear most nearly to resemble the nodules of either the red or the gray tuff phases are those in the figure accompanying Johannsen's (1937, pp. 300-301) discussion of variolites. The most detailed description of variolites is found in Rosenbusch (1908, pp. 1280-1288). These authors, however, confine the use of the term "variolite" to basic rocks in the basalt-diabase range on which spheroidal masses appear during weathering. The highly siliceous constitution of the two rocks under discussion makes the use of "variolite" seem inappropriate.

Stearns and MacDonald (1946, pp. 21 and 105) and Jaggar (1947, pl. 42-B, facing p. 467) have presented brief discussions of "ball lavas" formed either by accretion of basaltic lava around blocky cores on the surface of moving aa flows, or by formation of shells of glassy lava about rock kernels, again in basic lava. While Jaggar's photograph of the ball lavas of the Kau desert bears a superficial resemblance to the spheroids in the red keratophyre tuff of northern Canelo Hills, the absence of cores from the red tuff nodules, and the difference in composition of the lavas involved, make a close analogy appear unjustified.

Iddings (1887, p. 36) in his discussion of lithophysae in Obsidian Cliff, Yellowstone National Park, argues that incipient crystallization has taken place while the enclosing mass

was still viscid. Anhydrous microlites of feldspar radiate from a center into a sphere of glass paste. Gases, principally water vapor, held as tiny bubbles within the magma aggregate into larger bubbles and act as superheated steam, facilitating the crystallization of all constituents of the magma with which they come in contact. After giving up all the contained gases, but before final crystallization of the glass paste, shrinkage occurs through reduction in volume, and the cracks commonly seen in lithophysae and in spherulites are formed. Iddings considers as evidence of pre-final solidification of the lithophysae the presence of tridymite, quartz, and fayalite on walls of cracks in the lithophysae. Iddings' discussion may bear on the formation of spheroidal structures in the keratophyre tuff of this paper, especially those showing concentric shells.

A closer analogy appears in Teall's (1888, pp. 336-338) discussion of "nodular felsites," in regard to which Teall says, citing earlier work by Cole and Bonney:

> "The 'nodules' lie in a felsitic matrix in which fluxion structure is often well defined. They may be solid or hollow. In the latter case, the cavities are often lined with quartz crystals. Sometimes the cavities have been entirely filled with quartz . . .
>
> "The nodules vary in size from that of peas to globes measuring four or five inches in diameter. They have sometimes been flattened by crushing. A soft black substance is occasionally found associated with them. It is sometimes arranged in concentric zones . . . "

Citing Iddings, Teall then summarizes Bonney's conclusions that the nodules have been formed in one of two ways: (1) by simple contraction and roughly concentric cracking during cooling, and: (2) by similar contraction which is determined by the presence of a cavity. In this case, as cooling proceeds, pressure of the gases within the cavity against the walls of the cavity rapidly diminishes. This reduction in pressure upsets a previous tendency toward equilibrium in the cooling glass paste, and contractile stresses result in formation of concentric cracks about the cavity.

Although Teal mentions association of "felsitic agglomerate" with the nodular felsites, it does not appear that the agglomerate contains any nodular structures. Nor have the present

authors found any descriptions of comparable spheroidal structures in fragmental volcanic rocks.

OTHER OCCURRENCES

Other occurrences of spheroidal structures in volcanic rocks of Arizona will be cited, although they have not been examined in detail. Near Castle Hot Springs, about twenty miles east of Wickenburg, Brady[1] has found a basalt containing almost perfectly spherical masses which range in diameter to a maximum of about one inch. These spheroids are darker in color than the matrix and stand out distinctly on freshly broken surfaces of the rock. Examination under the microscope indicates that alteration controls these forms. Clay alteration is present in the spheroidal structures and not in the matrix.

[1] Brady, L. F., Letter and specimen (1947).

Spheroids are known to occur in considerable numbers in the dacite near Superior mining area, Arizona, but apparently have not been discussed in the literature.

Well-rounded, white tuff balls have been sent to the Arizona Bureau of Mines from an unspecified locality near Wickenburg, Arizona. Their field occurrence is not described. Each has at its center an elongate core. The spheres range from about one-half inch to two inches in diameter.

An outcrop of gray volcanic agglomerate abounding in xenoliths of various rocks, as much as several feet in maximum section, occurs beside the Tucson-Ajo road ten miles southwest of Tucson. Small-scale quarrying operations have exposed the rock. Scattered through it appear spheroidal masses, centered about xenolithic or calcareous cores. Bleached zones, nearly circular on weathered surfaces, but not showing spheroidal development, are associated. The entire occurrence strongly suggests analogy with the gray tuff spheroids described earlier from northern Canelo Hills. The development of spheroidal structures, however, appears less advanced in this quarry than in Canelo Hills.

PETROGRAPHY

Under the microscope the matrix enclosing the red spheroids is seen to consist of a very fine-grained mass of quartz and feldspar, formed through the devitrification of glass. The absence of quartz phenocrysts and the presence of phenocrysts of secondary albite suggest the term keratophyre or kera-

tophyre tuff. The characteristis texture of a welded tuff is strikingly shown by the matrix (pl. 1, fig. 2).

Plagioclase phenocrysts in the matrix have been altered to albite. Spherulites are scattered throughout the matrix as small bodies, some well-formed and others quite irregular in shape. Typical shadow-crosses are seen under crossed nicols. Small veins of secondary quartz traverse the matrix in a few places.

Although the flow structure cuts across the line of demarcation at the edges of the spheroids, the texture is distinctly finer in the spheroids. "Ghosts" of the welded tuff texture are present in a few places. Aggregates of feldspar and quartz are aligned in the direction of flow movement, and are much more widely spaced than in the matrix where, apparently, devitrification has not been as complete.

Alteration is similar in spheroids and matrix. The few plagioclase phenocrysts have been altered to albite and veinlets of secondary quartz are present. Spherulites seem somewhat more abundant in the spheroids than in the matrix, and tend to clump together similarly, merging into one another.

Equatorial thin sections up to 2 x 3 inches were prepared to show internal relationships of the ball structures, but attempts to include in one section the boundaries of matrix and spheroids proved futile. As seen in the field, flow structure appears to cut directly across both matrix and spheroids. This has not been confirmed microscopically.

The only suggestion that a radial structure may be the controlling influence on the prominently weathering forms is a spacing of quartz-feldspar aggregates defining the primary flow texture (fig. 1). A suggestion of "paths" progresses radially from the centers of some of the sections examined toward the periphery. Under crossed nicols these darker "paths" are outlined by more intense light transmitted by the coarser quartz-feldspar aggregates between. Viewed with the polarizer alone, slightly greater relief of the aggregates causes them to stand out as oriented islands. The origin of this phenomenon is unknown.

POSSIBLE MECHANICS OF ORIGIN

On the assumption that the matrix surrounding the red spheroids is a welded keratophyre tuff formed by accretion of

viscid lava particles, one possible explanation of these spheroidal structures is that they were extruded as larger and perhaps more fluid masses than the rest of the tuff. By virtue of their greater fluidity they might have been more completely bonded together at the time of ejection. Immediate burial by another layer of lava or by additional fluid ash material and

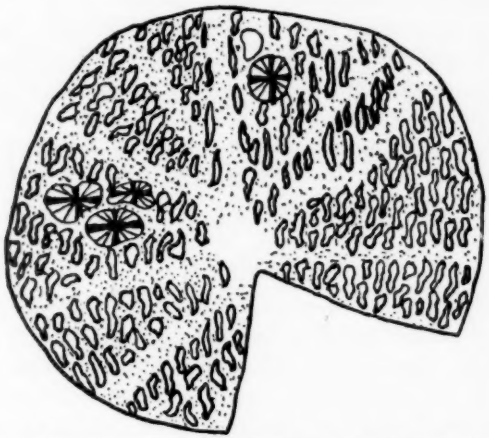

Figure 1. Diagrammatic representation of "paths" developed among oriented quartz and feldspar grains in groundmass of welded tuff spheroids, suggesting radial development.

subsequent movement of the whole mass down a slope would produce flow structure in matrix and spheroids alike, with textures differing according to the characteristics of the materials involved. One would not, perhaps, expect to find in structures formed in this manner the high degree of sphericity exhibited by the red spheroids, as partial rolling would tend to flatten the larger bodies.

Re-heating of a welded tuff or flow might tend to cause more highly siliceous areas to become less viscous sooner than the more basic remainder. Re-solution of the tuff starting from more highly siliceous centers would tend to change the character of the rock radially away from these loci. The assumption must here be made that the welded tuff, as laid down, was not completely homogeneous; areas more siliceous than the main mass were scattered throughout the flow, and after the tuff had become compacted, welded, and perhaps cooled (but

not crystalline), another thick flow moving over it would supply the heat necessary to start the melting only in the more siliceous areas.

Such incipient re-solution could probably destroy the flow structure of the welded tuff to the extent that it took on a finer-grained appearance, and "ghosts" of the coarse welded tuff texture might be left here and there.

If the silica present were in the form of quartz, this process probably would not take place, as the amount of heat required to melt the quartz crystals would be greater than that needed to melt the glassy matrix.

The presence of small amounts of water locally in the tuff would tend to lower the melting point greatly and have the same effect as more highly siliceous areas in remelting the tuff.

GRAY TUFF

The gray spheroids are seen under the microscope to be a typical tuff consisting of a fine-grained matrix with sporadic glass shards. Devitrification has been nearly complete. Most of the sections cut have masses of interlocked calcite grains completely occupying the central portion (pl. 2, fig. 2). Some of these calcite masses show evidence of zoning as if the calcite had been introduced from the outside to fill a vug or to replace some other material. Others show no evidence of this.

Both the matrix tuff and the spheroidal masses contain a great deal of calcite scattered at random throughout. Some of the spheroids have masses of calcite as large as their cores out near their peripheries.

The presence of "valleys" between layers of silica in the zoned quartz crystals mentioned earlier may be explained by calcite deposition alternation with the waves of silica deposition, provided that the calcite layers were subsequently removed by solution. The close proximity in the field between the limited area in which zoned crystals have been found and that in which the gray tuff nodules occur suggests a related secondary origin for both. No additional lines of evidence supporting such a hypothesis have been found. The writers feel that for the keratophyre nodules, however, the conclusion that they are of primary origin better satisfies the known facts.

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THE ULTRABASIC ROCKS OF MIDDLE RIVER RANGE, B.C.*†

H. W. LITTLE

ABSTRACT. The ultrabasic rocks of the Middle River Range of British Columbia consist of sills and stocks of dunites and peridotites, with minor pyroxenite and norite. Field evidence indicates that the ultrabasic rocks were probably derived from a magma of peridotitic composition. It is believed that the solutions which brought about partial to complete alteration of the ultrabasic rocks to serpentine were derived in part from the ultrabasic magma and in part from the intruded sedimentary rocks. The migration of solutions from the country rock into the intrusives results in cooling of both the country rock and the intrusives and is responsible for the low grade of metamorphism surrounding these ultrabasic bodies.

INTRODUCTION

As a result of the need for chromite and other war minerals, field parties were organized by the Geological Survey of Canada in 1942 to prospect for this mineral. Dr. J. E. Armstrong was assigned to the ultrabasic massif of the Middle River Range, and the writer was in charge of a sub-party in the west half of the area. This provided an unusual opportunity to study the ultrabasic rocks in great detail, and although it was not intended that an official report be published, such a wealth of additional knowledge of this area was obtained that the writer feels a report is justified.

LOCATION OF THE AREA

The Middle River Range lies between Trembleur Lake and Takla Lake in central British Columbia. The area mapped extends from latitude 54° 48′ to 55° 01′ and from longitude 125° 08′ to 125° 30′. It is approximately 300 square miles in area. (fig. 1)

PREVIOUS WORK

The first reference to any part of the region mapped was by Camsell (1916, pp. 70-75) who made a rapid reconnaissance trip along part of Trembleur Lake and Middle River.

In 1937, Armstrong (1941), while carrying out the reconnaissance mapping of the West Half of the Fort Fraser area, discovered and outlined the ultrabasic rocks. In 1940, he

* Part of a thesis submitted to the University of Toronto in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

† Published by permission of the Chief Geologist, Geological Survey of Canada.

mapped the rocks of the adjoining Takla sheet (Armstrong, 1946), north of latitude 55° 00′.

ACKNOWLEDGMENTS

The writer takes great pleasure in thanking all those who have given their assistance in the preparation of this work. He is especially grateful to Dr. J. E. Armstrong for the use

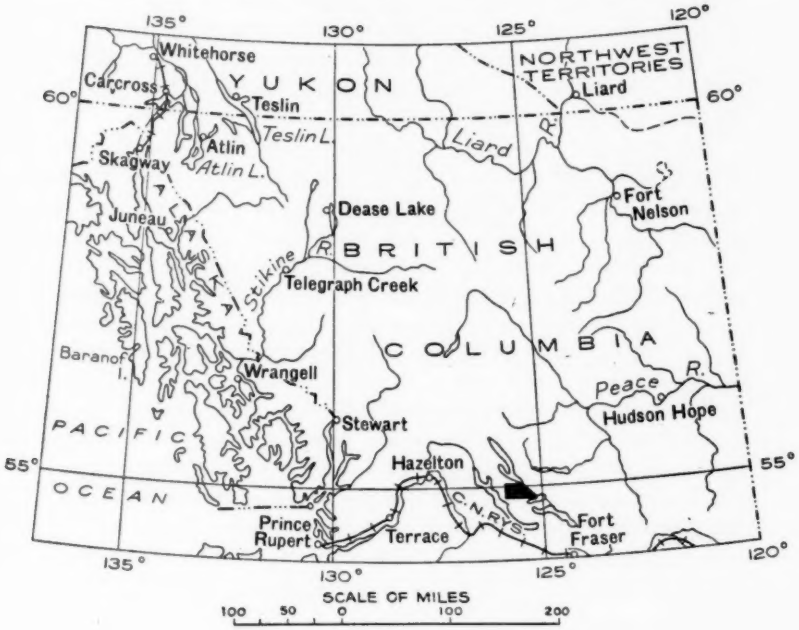


Fig. 1. Location of the area.

his field notes, specimens, and maps, and for the loan of many thin sections. In the west half of the area Mr. D. Carlisle rendered very efficient assistance to the writer during the field season.

At the University of Toronto, Drs. E. W. Nuffield, F. G. Smith and W. W. Moorhouse offered many valuable suggestions and other material contributions.

Although the views of the writer differ from those of Drs. N. L. Bowen and T. F. W. Barth, he is greatly endebted to them for a critical review of the manuscript.

GENERAL GEOLOGY

The oldest rocks in the area are presumably the Cache Creek series of Permian age, representing a comformable succession, not less than 22,000 feet of interbedded sedimentary and volcanic rocks and their derived metamorphic types. There are three divisions; a lower group of massive recrystallized limestone, a middle group of slate and argillite, with minor limestone and greenstone and related schists, and an upper group of greenstone, with lesser argillite, slate and minor limestone. All members strike northwest and have been tightly folded, the dips normally being steep. Regional metamorphism of the series is widespread and quite intense.

The Permian rocks have been intruded by Mesozoic (?) stocks, sills, and dykes, ranging in composition from ultrabasic to acidic. The ultrabasic bodies, which are older, are in general highly serpentinized and sheared, and have, in places, been altered to carbonate-talc-quartz rocks. These rocks were originally mainly peridotites and dunites, with minor pyroxenite and norite. The acidic bodies are composed of soda granite, quartz porphyry, and minor related acidic and basic dyke rocks.

The extreme western part of the area is underlain by a great thickness of sedimentary and volcanic rocks of the Takla group, which is Jurassic and possibly Upper Triassic in age. These rocks are intruded by acidic stocks and dykes, but in no place are they cut by rocks of ultrabasic composition.

A widespread mantle of Pleistocene and Recent material which covers much of the area was not mapped.

ULTRABASIC AND RELATED INTRUSIVES

The oldest group of intrusive rocks in the area consists of peridotites, dunites, pyroxenites, and norites in descending order of abundance. Owing to the small size and complexity of the segregated bodies, most of them cannot be separated on the map. For this reason areas have been classified on the map according to the rock type which predominates in that particular locality.

In general, nearly all of these interrelated rock types are considerably altered—the olivine to serpentine and magnetite, the pyroxenes to amphiboles, serpentine, and magnetite, and the plagioclase, which appears only in the norite, to saussurite.

The ultrabasic complex is estimated to consist of more than 75 per cent peridotite in the east half of the area, but in the west half where differentiation into dunite and peridotite is more marked, it consists of only about 65 per cent peridotite. Those peridotites which have not suffered hydrothermal alteration are dark green, medium-grained rocks, usually containing from 10 to 60 per cent pyroxene, the average being nearer the lower figure. In addition to pyroxene, the peridotites contain olivine, with minor amounts of picotite, chromite, or magnetite.

The peridotites are predominantly of the saxonite or harzburgite type. A few of the wehrlite type were observed, but none of the lherzolite type. The pyroxene crystals are generally much larger than those of olivine, which are sometimes encased

Table of Formations

Age	*Name*	*Description*
Pleistocene and Recent		Recent alluvium and glacial drift (moraines and erratics).
Post-Jurassic and (?) Pre-Upper Cretaceous		White soda granite, pink biotite granite and related dyke rocks.
	Tsitsutl stock	Quartz porphyry and related dyke rocks.
Jurassic and (?) Upper Triassic	Takla group	Andesite and basalt flows, tuffs and breccias, with interbedded sandstone, shale and conglomerate.
Post-Permian and Pre-Upper Triassic	Trembleur intrusions*	Peridotite and dunite, with minor pyroxenite and norite, and related alteration products — serpentine and carbonate-quartz-talc rocks.
Permian	Cache Creek series	Andesite and rhyolite flows and tuffs, with lesser argillite and slate and minor limestone.
		Argillite and slate, with minor limestone and greenstone and related schists.
		Massive dark grey recrystallized limestone.

* The name "Trembleur intrusions" has been applied by J. E. Armstrong to many bodies of ultrabasic rocks of probable pre-Upper Triassic age that are exposed in the Fort St. James Map-Area, B.C., Geol. Surv., Canada (memoir in press).

in pyroxene, giving rise to poikilitic texture. In this case the pyroxene is often altered to serpentine, whereas the smaller olivine crystals are virtually unaltered. Where the olivine crystals are larger, and the proportion of pyroxene is less than average, the olivine appears to be as readily altered as the pyroxene. Olivine is usually altered to antigorite along regular fractures in the crystal. Orthorhombic pyroxene on the other hand frequently appears to have been partly altered to thin laths of tremolite along the prominent cleavages, and later the remainder was altered to antigorite. Augite, however, was altered partially to uralite in only one case, and never to serpentine.

The dunites as a rule are darker in colour than the peridotites and somewhat finer in texture. On the weathered surface they present a buff-coloured, granular appearance. The dunites appear in sills, and as irregular zones or bands between similar zones of peridotite in thick, differentiated sills, or as irregular masses in the batholithic body underlying Mount Sidney Williams.

The dunites may be seen in thin section to consist of coarse grains of subhedral olivine, usually considerably altered to antigorite, and minute grains of picotite, chromite, or magnetite are common.

The pyroxenites are in general rather coarser in grain than the peridotites and present a fibrous appearance. They are green in colour and may be almost fresh, or they may be nearly completely altered to serpentine with or without the presence of uralite or tremolite.

Thin sections show that the pyroxenites are composed essentially of large crystals of pyroxene more or less altered to antigorite and magnetite. Partial alteration of the pyroxene to hornblende or tremolite may also have taken place.

Pyroxenites occur as lenticular masses of limited size either in peridotite or dunite, or in the pyroxenite-norite complexes which occur in the east half of the area. They form also extremely coarse-grained branching dykes, varying in width from a fraction of an inch to two feet, cutting across the primary banding of the peridotites.

The norites are highly altered dark green medium-grained rocks. The presence of plagioclase feldspar distinguishes them from other rocks of the ultrabasic complex.

The rock in thin section is observed to consist of pyroxene, usually completely altered to amphibole, magnetite and epidote, and of plagioclase which is highly saussuritized. In a few in which the pyroxene is sufficiently fresh to be identified, it was found to be hypersthene. Primary magnetite is present in some specimens. The norites occur only in the east half of the area either in the pyroxenite-norite complexes, or as altered dykes up to 30 feet in width cutting the peridotites on Mount Sidney Williams.

Internal Structures of the Ultrabasic Rocks. The relationships between the different rock types in the ultrabasic complex are of paramount importance in an analysis of their origin. Within the northern part of the ultrabasic batholith, that part underlying Mount Sidney Williams, dunite forms irregular masses (fig. 2) varying from a few square feet to several thousand square feet in area within the peridotite. These masses have no regular distribution, and are as numerous near the borders as they are in the interior of the batholith. The peridotite-dunite contacts are gradational across 2 to 4 inches. It has been estimated that within this moderately altered part of the batholith dunite probably exceeds one quarter of the total mass.

From the peak of Mount Carlisle eastward to their contact with greenstone, the ultrabasic rocks consist of thick differentiated alternate layers of dunite and peridotite, the latter predominating. Within this locality there are six sill-like differentiated zones of dunite in the peridotite. These zones, which strike about north-south and dip vertically, are from 50 feet to 100 feet wide and can be traced longitudinally for several hundred feet, their extremities either terminating in precipitous cliff faces or else disappearing under a cover of drift. Within this massive dunite, the olivine is often coarse-grained and considerably serpentinized. The dunite has a typical yellow-brown sandy weathered surface. Chromite is common as an accessory, varying from 1 per cent to more than 5 per cent. In the latter case it forms nodular masses up to three-eighths inch in diameter, from which thread-like veinlets of chromite extend for several inches. It was noted in the field that in these zones the chromite content increases appreciably at lower elevation; this gradation is therefore perpendicular to the walls of the zones.

In the stock three miles south of Pyramid Peak and in the broad sill south of Tsitsutl Mountain, primary banding of the peridotite is striking, and is clearly visible from considerable

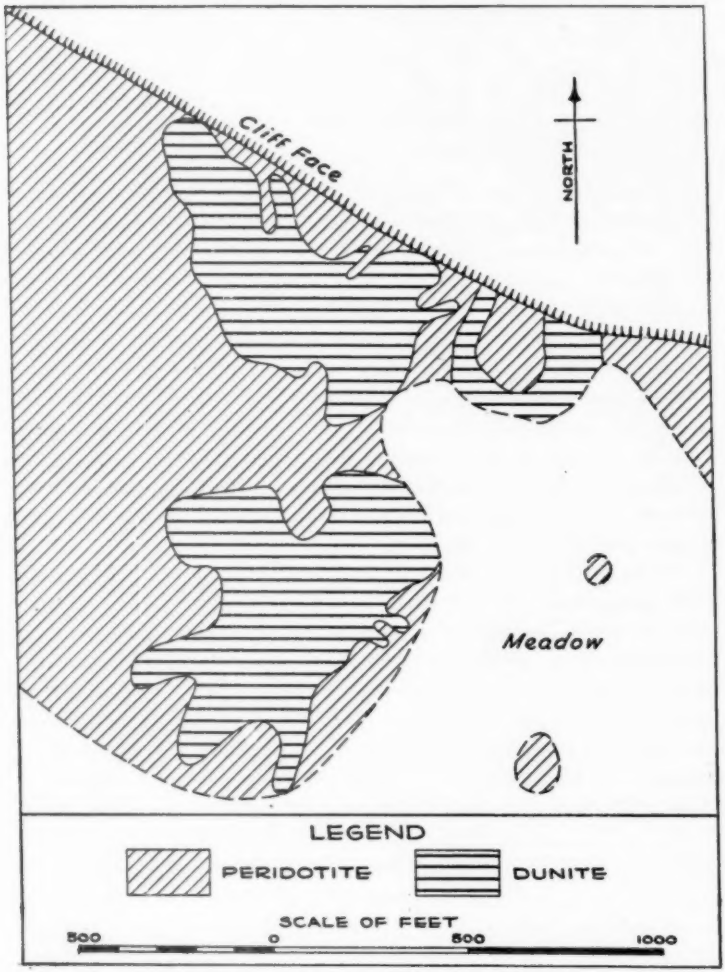


Fig. 2. Irregular masses of dunite in peridotite on Mt. Sidney Williams.

distances. Detailed examination of the layers reveals that they are usually about 2 inches thick, consisting of peridotite containing about 10 per cent pyroxene, separated by peridotite

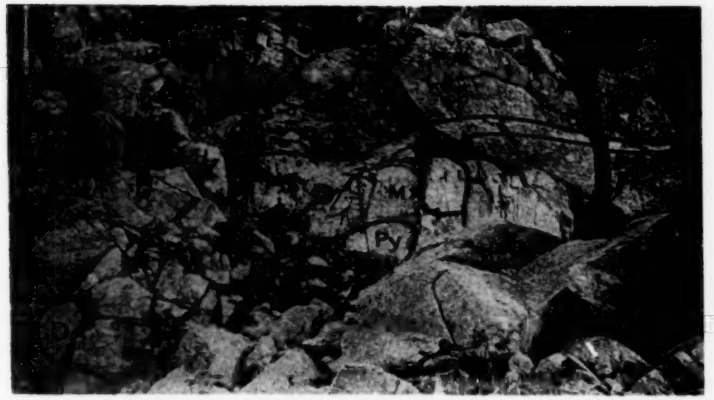


Fig. 1. Irregular dunite mass cutting across primary banding in peridotite. P - peridotite, D - dunite, Py - pyroxenite, M - magnetite.

Fig. 2. Pyroxenite dykes cutting peridotite on Mount Sidney Williams.

with about 40 per cent pyroxene, and approximately 1 foot in thickness. The base of each narrow band is sharp, but the top is gradational across ½ inch, which is indicative of crystal settling. Frequently the pseudostratification of the peridotites is gently curved, suggesting a bending while still plastic, and tiny fractures show displacements of several inches, which gradually decrease to zero a few feet distant on the outcrop faces. The outcrops of banded peridotite appear to form separate blocks whose attitudes vary from one to another as though separated by minor faults.

In the thick sill dunite, in addition to occurring as segregated layers, forms small, irregular bodies with long apophyses into the peridotite. The contacts, however, are seldom sharp, and never knife-edge, possibly owing to reaction between the two rock types. In dunite of this type, magnetite is a common accessory, rather than chromite. One such body is noteworthy for its peculiar structure. It consists of a bulbous mass of fine-grained dunite about 5 feet in diameter, which grades toward the centre into a coarse pyroxenite. A small mass of magnetite lies just above the pyroxenite. An apophysis of dunite nearly 15 feet long and a few inches wide extends from the bulbous mass across the primary banding of the peridotite host-rock (pl. 1, fig. 1).

On Mount Carlisle, in addition to occurring as broad zones, dunite forms lenticular masses up to 5 feet or more wide and at least 10 feet long. The non-parallel walls are in rather sharp contact with the peridotite so that they appear to be later in age than the latter.

Dunite also occurs as sills such as the one which lies about 1 mile west of West Peak. While no peridotite occurs in these sills, lenticular masses of pyroxenite up to more than 100 feet in length are often present. They are rather coarse in texture, the majority of pyroxene crystals exceeding ¼ inch in length. The pyroxenite grades within a few inches through a peridotitic phase into dunite.

In the broad sill south of Tsitsutl Mountain, where the pyroxene content of peridotite is high (60 to 70 per cent), irregular xenoliths of peridotite containing perhaps 30 per cent pyroxene are often present. These xenoliths stand out clearly on the outcrops because of their fine-grained texture and particularly because of the rusty weathering of the sur-

face in contrast to the typical orange-weathering of the peridotite that encloses them.

Near Mount Sidney Williams several lenses of pyroxene-rich peridotite up to 500 square feet in area were observed in the peridotite. These have gradational contacts across a few inches with normal peridotites.

Pyroxene-rich peridotite and pyroxenite occur also in dykes which intersect the ultrabasic complex in the same locality. These dykes are irregular and branching, varying in width from a fraction of an inch to more than a foot (pl. 1, fig. 2). Similar dykes as much as two feet wide were observed near Mount Carlisle. They consist of extremely large crystals of pyroxene which grow perpendicular to the walls of the dykes. In such dykes chromite is present in minor amount and is always clearly interstitial. In one dyke pyroxene was brecciated and chromite forms a sparse cementing material.

One of the bodies underlying West Peak is composed almost entirely of a norite-pyroxenite complex. A similar complex occurs near Trembleur Lake and is completely surrounded by carbonate-quartz-talc rock. The norite appears to be relatively fresh in the hand specimen, and consists of about one-half white feldspar, the remainder being short, prismatic crystals of pyroxene. It is intimately associated with small masses of very coarse-grained pyroxenite. Both of these rocks are very little affected by the carbonate solutions which have replaced the peridotites and dunites in the vicinity. Thin sections of the rocks reveal, however, that the plagioclase has been somewhat saussuritized although the hypersthene is little altered. Several small outcrops of pyroxenite occur elsewhere within the carbonate-quartz-talc rocks.

In the vicinity of Mount Carlisle north-south fault zones 25 to 100 feet wide traverse the serpentinized ultrabasics, displacing acidic and basic dykes that cut the serpentine. They are recognizable as zones of schistose serpentine in which slickensides are common. In many cases ellipsoids of massive serpentine up to several feet in diameter occur in the zones. The schistose serpentine throughout the faults is usually light green and sometimes this effect is noticeable on the outer half-inch of the ellipsoids. Such light-green serpentine does not weather on the surface to the typical orange or yellow-brown of the normal dark serpentine.

Serpentinization of the Peridotites, Dunites, and Pyroxenites. The peridotites, dunites, and pyroxenites have undergone partial to complete alteration to serpentine, so that in thin section it is often impossible to determine the original constituents of the rock. In hand specimens, however, pseudomorphs of serpentine after orthorhombic or monoclinic pyroxene are easily recognized by cleavage faces on the broken surfaces, or by outlines of the crystals on the weathered surfaces. The serpentine is mainly antigorite and is generally olive green, except in fault zones where it is often light green, or in contact with acidic dykes where it assumes a characteristic chocolate brown colour. The fibrous variety of serpentine, chrysotile, is often observed in minute fractures and in fissures, where it may attain a length of 10 inches or more. No chrysotile of commercial quality has been found in the Middle River Range; that which does occur is much too brittle.

The progress of serpentinization has been described in detail by Armstrong (1940, pp. 21-32), and the writer does not need to reiterate his statements. Certain additional observations were made during a study of thin sections and these are as follows:

1. In general, dunite is most highly serpentinized, the olivine being generally almost completely altered to serpentine; the original rock is recognized largely by means of its characteristic texture. Serpentinization of peridotite varies from virtually no alteration to almost complete alteration. Where the texture of peridotite is equigranular, olivine is invariably more completely altered than pyroxene, but where the texture is poikilitic the large pyroxene crystals are often completely altered to serpentine, while the smaller olivine crystals which are encased in the pyroxene are practically unaffected. In pyroxenites the pyroxene is sometimes quite fresh, but more often it is partly altered to amphibole and serpentine.

2. Previous to serpentinization, orthorhombic pyroxenes have in many cases partially undergone what is apparently deuteric alteration to amphibole. This effect took place along the cleavages of the pyroxenes. Where serpentinization accompanied or followed this process, acicular crystals of tremolite with a common orientation mark the positions formerly occupied by pyroxene.

Facts pertaining to serpentinization of the ultrabasic rocks of the Middle River Range are enumerated below:

1. Serpentinization is invariably more complete in small ultrabasic bodies, especially those of dunite, than in those of larger size.

2. Serpentinization is more intense within fault zones than in unsheared ultrabasic rocks. While this fact at first sight appears to favour an hydrothermal source for serpentinizing solutions, it may be explained by the fact that those parts of the ultrabasic bodies that have been most highly serpentinized were the most incompetent and therefore tended to localize shears resulting from stress. This would be true particularly if serpentinization were accompanied by a decrease in volume.

It has been noted previously that in the majority of shear zones in the ultrabasic rocks, there is present a spotted light-green serpentine which does not exhibit the usual orange-weathering limonitic coating of normal dark green serpentine. Schistose serpentine is as a rule completely altered to the light-green variety, but where ellipsoids of massive serpentine are present in a shear zone this alteration does not penetrate more than one-half inch from the surface of the ellipsoids. Such bright green serpentine is believed by the writer to be the effect of leaching of the iron oxides, which have been carried away. This removal of iron oxides was apparently accomplished by hydrothermal solutions ascending the fault zone, since in one locality a network of tiny calcite veinlets has been introduced into fractures in the serpentine.

3. The distribution of serpentinization bears no relation to the proximity of younger acidic intrusives that traverse the ultrabasic bodies. It is therefore evident that serpentine was not produced by hydrothermal solutions emanating from the acidic intrusives themselves.

Armstrong (1939, pp. 77-78) has reviewed the development of the various theories that have been proposed to explain the processes of serpentinization of ultrabasic rocks. He has shown that the more recent investigators favour an autometamorphic process in which serpentinizing solutions accumulate within the ultrabasic reservoir and migrate to the consolidated portions, altering the olivine and pyroxene to serpentine. Hess (1933, pp. 634-657; 1938, pp. 321-324) has further modified this conception by suggesting that the serpentinizing reaction was

not only auto-metamorphic, but deuteric in the most restricted sense. He also offers the suggestion that if water-bearing sediments have been intruded by ultrabasic rock the former will probably contribute additional water to the serpentinizing solutions. He apparently believes that this contribution is of minor significance, since he suggests that the ultrabasic magma contains from 5 to 15 per cent water, the latter quantity being more than sufficient to bring about complete serpentinization of dunites and peridotites.

Morey and Ingerson (1938, pp. 217-225) have shown that at high temperatures and pressures, water and alkali silicates are mutually soluble in all proportions. Goranson (1938, pp. 71-91) has found that the maximum solubility of water in albite melts and in glasses of Stone Mountain granite is approximately 10 per cent. Smith (personal communication) believes that the solubility of water in silicate melts bear a direct relation to the alkali content of the melt, so that by extrapolation of the solubility curve, the maximum solubility of water in a melt of ultrabasic composition would probably not exceed 2 or 3 per cent. If this were the case, the serpentinizing solution could not have originated entirely within the ultrabasic magma.

Field evidence indicates that the injection of the ultrabasic magma began when the sediments that they intruded were still flat-lying, or nearly so. It is therefore probable that the sediments contained a considerable amount of water, a large proportion of which may have contributed to the serpentinization of the ultrabasic rocks. This hypothesis most clearly explains why the smallest bodies of ultrabasic rocks are the most completely serpentinized.

Hess (1933, p. 651) and Cooke (1937, p. 67) have listed several of the most probable chemical reactions by which dunites, peridotites, and pyroxenites may be altered to serpentine. In such reactions, where serpentinizing solutions have been introduced there results an increase in volume of from 25 to 84 per cent. If the serpentinizing solutions were present in the original magma, only small volume increases, and in some cases, volume decreases occur during serpentinization. If a portion of the solutions was derived from the magma and the remainder from the country rock, it is approximately equivalent to assuming that all the solutions came from the

magma, since the shrinkage of the country rock upon dehydration would tend to compensate for the expansion brought about by serpentinization. Therefore it is unlikely that serpentinization brought about a very great expansion of the rocks as a whole, and this expansion would express itself in faulting and other small movements. The serpentinizing solutions consisted mainly of water, derived in part from the ultrabasic magma itself, in part from the intruded rocks. In the latter case, alkaline silicates and carbonates were probably present in aqueous solution.

Steatitization of Dunites, Peridotites, and Pyroxenites. Steatitization of the serpentinized dunites and peridotites is so extensive in the east half of the Middle River Range that the altered rocks have been mapped as a separate petrographic unit. From a study of the map it can be seen that the most extensive alteration of this type occurs around the periphery of the ultrabasic batholith, particularly toward the southeast. The best exposures occur along Trembleur Lake and the ridge to the northwest which parallels the shore.

The hydrothermally altered rocks are greenish grey to buff and consist of buff-coloured carbonate, pale green talc, and white quartz in various proportions. Euhedral to subhedral grains of magnetite and chromite are often present as accessory minerals. Occasionally a chrome-bearing, apple-green mica (mariposite) is observed, and euhedral crystals of pyrite are less common. Armstrong (1940, p. 32) has reported chalcopyrite as an accessory mineral, but it was not seen in specimens examined by the writer.

The carbonate-talc-quartz rocks replace serpentine most easily; slightly serpentinized pyroxenites are least affected.

Armstrong (1940, pp. 30-31) has stated that the hydrothermally altered ultrabasic rocks can be divided into two distinct types: a carbonate-quartz-mariposite type and a carbonate-talc type. This implies that where quartz or mariposite are present, talc should be absent. The writer believes that no such classification is possible. Where alteration is slight, small quantities of talc or carbonate or both may be found in the rock. Where the alteration is more advanced, quartz may also be present. Where replacement of the original peridotites or dunites is complete or nearly so, the rock con-

sists of at least three minerals: carbonate, talc, and quartz. The chrome-mica mariposite was found by the writer in only two thin sections, where it is associated with quartz and carbonate; talc is lacking although it is abundant in specimens taken nearby.

The carbonate which is abundantly present in most of these altered rocks is buff-coloured and weathers to a yellow-brown coating of limonite. Two samples of the carbonate were analyzed by the writer, who found that they are entirely lacking in calcium and manganese. The composition lies between that of magnesite, $MgCO_3$ and mesitite, $MgFe(CO_3)_2$.

This type of alteration was most probably brought about by the attack of dilute carbonate solutions upon serpentine. The chemical reactions may be expressed in this manner:

$$\underset{\text{serpentine}}{2H_4Mg_3Si_2O_9} + 3CO_2 = \underset{\text{talc}}{H_2Mg_3(SiO_3)_4} + \underset{\text{magnesite}}{MgCO_3} + 3H_2O$$

$$\underset{\text{serpentine}}{3H_4Mg_3Si_2O_9} + 3CO_2 = 3\underset{\text{magnesite}}{MgCO_3} + \underset{\text{quartz}}{SiO_2} + 2H_2O$$

The iron, which is always present in the carbonate, must have been derived from the magnetite everywhere present in the serpentine. The water released by both reactions would serve to serpentinize the ultrabasic rocks above, which had not been completely altered to serpentine, and prepare them for alteration to carbonate, talc, and quartz.

Both of the above reactions have taken place during serpentinization, although locally one or the other may predominate. Temperature may be the chief factor governing these reactions, but a glance at the equations suggests that where carbon dioxide is abundant the formation of talc and carbonate will be favoured, rather than that of carbonate and quartz. From a study of the thermo-electric potential of the euhedral pyrite crystals present in two hand specimens of carbonate-quartz-talc rock, F. G. Smith determined their temperatures of formation to be approximately 450° and 500° C. respectively (1943, pp. 519-523).

The contacts of all ultrabasic rocks have undergone steatitization. This is probably due to the migration of hydrothermal solutions induced in the invaded rock by the intrusive rock. Such solutions would no doubt contain carbonates which would react with the chilled margins of the ultrabasic bodies, where

the temperature may be favourable to such reactions. Similar steatitization penetrating several inches into ultrabasic rocks was seen where they have been invaded by acidic dykes, but this form of alteration has not always taken place.

An underlying magma is postulated as the source of the hydrothermal solutions that brought about the steatitization of the major part of the ultrabasic batholith. The composition of this magma is not known, since no known off-shoots from it are exposed in the locality.

Metamorphism of Invaded Rocks by Ultrabasic Bodies. One of the most controversial subjects with regard to the origin of ultrabasic rocks is the general lack of metamorphism surrounding intrusives of this composition. The first step in an analysis of this problem is to determine the temperature at which the ultrabasic rocks were intruded. Bowen and Schairer (1935, pp. 151-217) have discussed the system MgO-FeO-SiO_2, and have shown that magmas having the composition of the ultrabasic rocks of the Middle River Range must be almost completely crystallized at 1500° C. in a dry melt. The authors point out, however, that the presence of a small amount of Fe_2O_3 in the system complicates the phase diagram greatly. The effect of other constituents is unpredictable, but it seems probable that the addition of potassium, sodium, calcium, and aluminum to the system would lower the melting intervals of the members by at least 100° C., and the addition of 2 to 3 per cent water, with small amounts of boron, fluorine, and chlorine would have an even greater effect. The effect of pressure at a depth of 5 miles would be to increase the melting point of peridotite about 50°.

The writer postulates that the ultrabasic magma was injected at a temperature of about 1200° C. This figure agrees with the estimate derived from field evidence by Ingerson (1935, pp. 422-440) in the Trout River area, Newfoundland.

On the assumption that the temperature of the invaded rocks was 100° C., the maximum temperature reached by any point in the invaded rocks surrounding a sill 400 feet thick was calculated by this writer (Ingersoll and Zobel, 1913, p. 70). The results are plotted in figure 3. It is apparent that the temperature of the invaded rocks more than 15 feet from the

contact of the sill never exceeded 600° C. In this particular sill the outcrop of host rock nearest to the sill is 50 feet from the contact, so that the maximum temperature reached at this point was only 529° C. The slates here are spotted, the spots consisting of radial fibres of tremolite in a fine-grained dark ground mass in which sericite, tremolite, and quartz can be recognized.

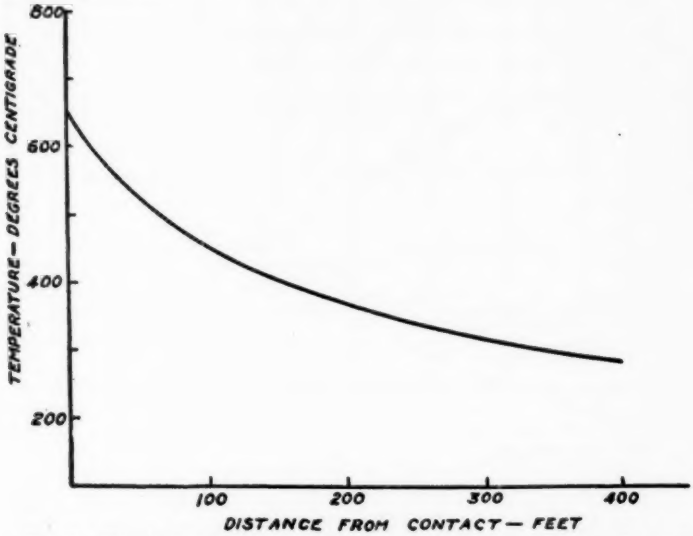


Fig. 3. Graph showing the maximum temperatures reached by the wall-rock originally at 100° C., after intrusion of a dunite sill at a temperature of 1200° C. and 400 feet thick.

Although it has no bearing on the problem, it is interesting to note that the maximum temperature of 609° C. reached at a point 12½ feet from the contact is attained 55 years after intrusion; that of 280° at 400 feet from the contact requires 799 years.

The ultrabasic batholith about which one would expect the greatest metamorphic effects is surrounded by an hydrothermally altered zone of talc and carbonate more than 100 feet wide, so that the contact effects here have been obliterated. The cooling curves for a lenticular or spherical igneous body 1000 metres in radius have been calculated by Ingersoll and

LEGEND

MESOZOIC

UPPER TRIASSIC (?) AND JURASSIC

TAKLA GROUP

Porphyritic and amygdaloidal lavas (andesite, rhyolite, basalt); argillite, sandstone and conglomerate

PALÆOZOIC

PERMIAN

CACHE CREEK GROUP

Andesite (greenstone) and rhyolite; minor argillite and limestone

Argillite and slate; minor andesite (greenstone) and limestone

Massive limestone, minor argillite and slate

MESOZOIC

Quartz porphyry

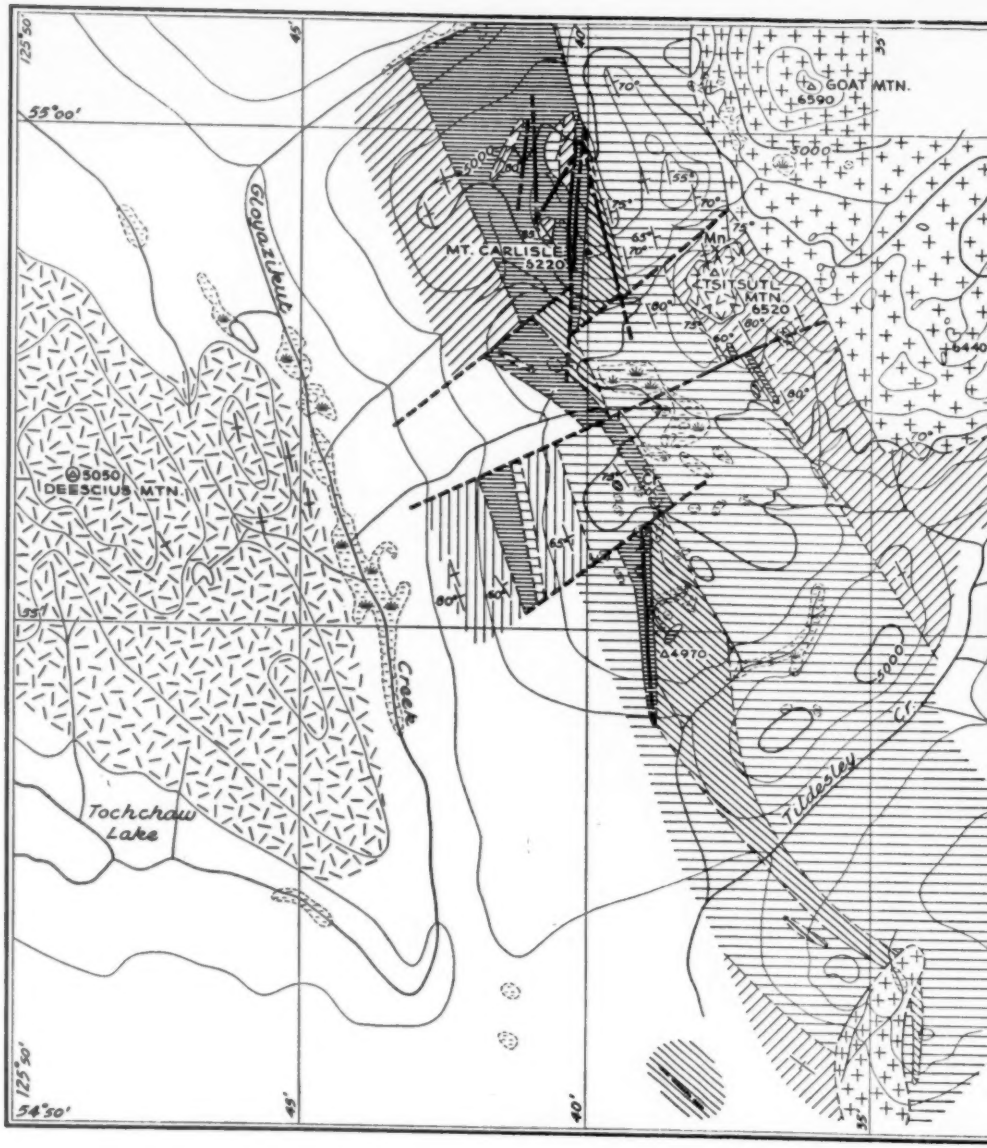
Biotite granite

Norite-pyroxenite complex

Predominantly peridotite, with dunite and minor pyroxenite

Predominantly dunite, with peridotite and minor pyroxenite

Carbonate-talc-quartz rocks (altered ultrabasic rocks)



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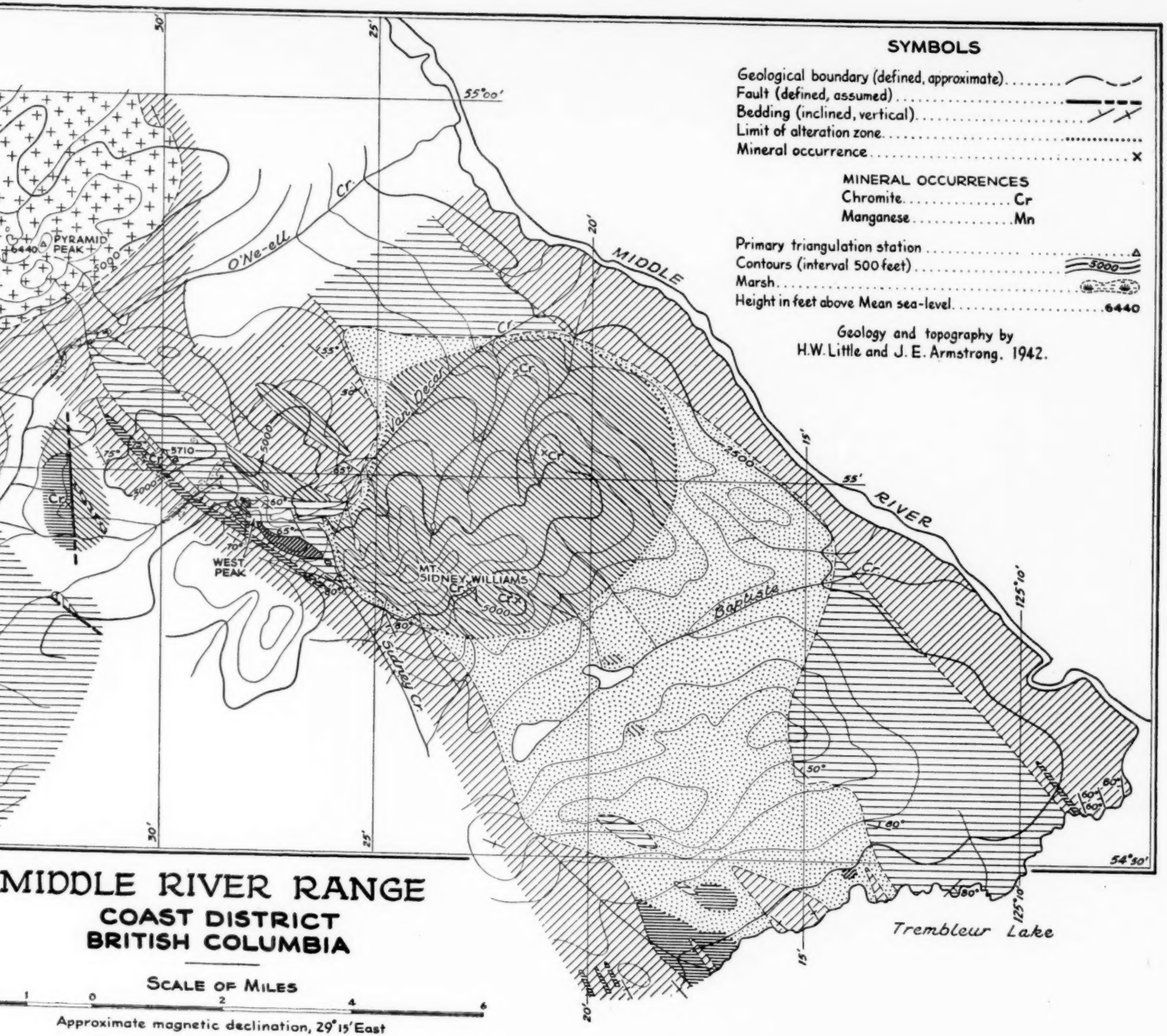

Fig. 5. Geological map of the area.

Zobel, and these are reproduced in figure 4. While the ultrabasic batholith is somewhat larger in dimensions, the effect would be similar.

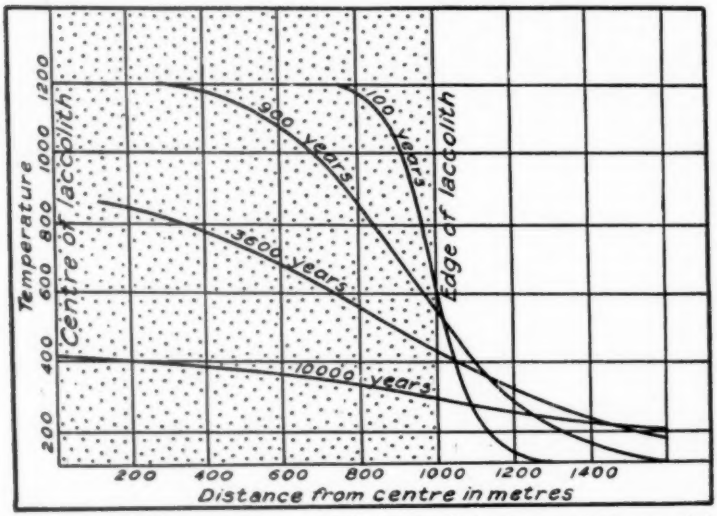

Fig. 4. Cooling curves of a spherical or lenticular igneous body intruded at 1200° C. into shales at 100° C. Radius of body is 1000 metres. (After Ingersoll and Zobel.)

The writer proposes that the ultrabasic magma was intruded at about 1200° C. into sediments that were comparatively rich in water. As the sediments reached their maximum temperature, hot aqueous solutions derived from them and containing alkaline silicates and carbonates, migrated into the cooling magma. At the chilled borders, where the temperature was much less than in the interior, the reaction favoured was that of conversion of the ultrabasic rock, and the sediments immediately adjacent, to talc and carbonate. The alkaline silicate solutions, which now contained little carbonate, migrated into the main mass of ultrabasic rock, which was at a higher temperature, and brought about serpentinization of olivine and pyroxene.

The preceding calculations cannot be applied to xenoliths, which must have been heated almost to the temperature of the enclosing rock, as heat would have flowed into them from all sides. Argillaceous xenoliths have been baked to an exceedingly hard, fine-grained aphanitic mass. The results should be similar, except for the effects of pressure, to heating the rock in an

open crucible, because the ultrabasic rocks would act as an absorbent of aqueous solutions. Where calcium and magnesium are present, tremolite is likely to be formed, but in the later stages of cooling retrograde effects may disguise the earlier high temperature effects. If potassium is present, sericite may be formed.

In one large xenolith a bed of limestone 5 feet thick has been wholly recrystallized to coarse calcite containing euhedral crystals of ilmenite. Considerable chlorite was also introduced into the rock. A sample of calcite was ground to —100 +200 mesh and heated in an electric furnace until the liquid inclusions it contained exploded. The temperature at which the explosions began was 295° C. at one atmosphere pressure. This corresponds to a temperature of 385° C. if the depth at which crystallization took place is assumed to have been 3 miles (Beland, 1946). A sample of ilmenite treated in the same manner indicated a temperature of crystallization only 2° lower. This temperature of 385° indicates the lowest temperature at which hydrothermal solutions deposited calcite and ilmenite. It is apparent that hydrothermal solutions were active in the ultrabasic rock long after the body itself began to cool.

The Origin of the Ultrabasic Rocks. A theory that would account for the origin of the ultrabasic rocks of the Middle River Range must satisfactorily explain the following features:

1. Sills composed almost entirely of olivine have parallel walls and tremendous length, indicating a high degree of fluidity for the magma that emplaced them. On the other hand, bodies consisting of peridotite or norite-pyroxenite are lenticular or oval in shape.
2. In the broad sill-like bodies of ultrabasic rocks, differentiation into zones of peridotite and dunite that are parallel to the walls of the sills has taken place before consolidation.
3. In the ultrabasic batholith dunite forms irregular bodies within the peridotite.
4. In some localities, dunite masses exhibit cross-cutting relationships to the peridotite.
5. Irregular, branching dykes of extremely coarse-grained pyroxenite and pyroxene-rich peridotite intersect the peridotite.
6. There is a distinct break in the petrographic sequence

of rocks from ultrabasic to acidic types; there are no representatives in the area of those types which lie between the norite-pyroxenite complex and soda granite. There is apparently also a time-gap of from 45 million to 140 million years between the time at which the ultrabasic and acidic rocks were emplaced, the latter having been injected after the former.

This complete lack of gradational phases between the two extreme groups of igneous rocks in the area, together with the relatively high proportion of ultrabasic rocks to acidic rocks precludes the acceptance of Bowen's theory (1928, pp. 133-174) of crystal settling from a basaltic magma to account for the origin for the ultrabasic rocks. The writer is forced to the conclusion that the ultrabasic rocks in the Middle River Range were derived from an ultrabasic magma whose composition closely approached that of the rocks derived from it.

The first invasion by this magma produced sills at a time when the sedimentary rocks intruded were still flat-lying, or nearly so. The magma was still in a highly fluid state. Sills of dunite were apparently formed at this stage by "filter-pressing". The interstitial liquid migrated farther than the olivine crystals, either during the initial intrusion or shortly afterwards, before the formation of pyroxene crystals could take place. Relatively small, lenticular pockets of the interstitial liquid did remain, however, and these produced lenses of hypersthene and augite.

Narrow bands of alternate olivine-rich and normal peridotite, 2 inches and 1 foot thick respectively, have been described on page 8. A theory that will satisfy the conditions noted in the field is that of periodic release of volatiles. As cooling proceeded, crystals of olivine would settle to the solidified part of the intrusive from the still fluid central part. A sudden release of volatiles would increase the melting point of the liquid phase, so that a layer of peridotite will suddenly solidify, trapping the olivine-rich layer at the base. Periodic repetition of this process would bring about the type of pseudostratification that has been described.

Just prior to the complete solidification of the thickest sills, orogenic movements were initiated. This brought about bending and minor fracturing of the semi-plastic pseudostratification. At the same time fluid material was injected from the hotter parts of the sills which would have been enriched in

volatiles owing to the crystallization of most of the silicates. Such magma would contain a large percentage of olivine crystals which would be filter-pressed to form lenticular masses of dunite cutting the peridotite. The interstitial liquid that had been filter-pressed out would migrate farther and form the coarse-grained pyroxene-rich peridotite dykes that have been described. That such a mechanism is plausible is seen in the intrusive mass of dunite described on page 9. In plate 1, fig. 1 it may be seen that the bulbous mass is tubular, and movement of this residual magma took place in a direction perpendicular to the face of the outcrop. During the movement of this magma, olivine crystals were deposited on the walls of the tube and in the apophysis that runs out from it. Later, as the magma cooled, pyroxene crystals were precipitated and these formed the central core. These pyroxene crystals are pegmatitic owing to the relative increase in the volatile content of the last part of the residual magma.

At or near the conclusion of the folding there occurred the final intrusion of magma from the ultrabasic reservoir. This magma was apparently more viscous than that which formed the sills. The intrusive bodies formed at this stage are lenticular or oval in shape, ranging in diameter from 30 feet to 7 or 8 miles. They consist predominantly of peridotite, although the largest bodies contain irregular masses of dunite within the peridotite. Regular banding of these peridotites is common.

These bodies must have been emplaced by thrusting aside the invaded rocks. They could not have been emplaced by stoping, because the ultrabasic magma had a greater specific gravity than the invaded rocks. Assimilation of the country rock could have taken place only on a minor scale, if at all, as shown by the presence of numerous xenoliths that have been little affected.

When the ultrabasic rocks were almost completely consolidated there must have remained a final liquid of relatively minor amount, which was injected to form a lenticular stock of norite-pyroxenite complex. Another mass about 1000 feet in diameter occurs within the ultrabasic batholith near Trembleur Lake. The relationship between this mass and the batholith is not known, since it is completely surrounded by steatitized rocks. A comparatively few dykes of norite were injected into the ultrabasic batholith perhaps at the same time. This

noritic material may have been present originally in the ultrabasic magma, or it may have been the result of assimilation of basalt or greenstone by the ultrabasic magma just prior to, or during injection.

The deuteric effects that took place during the final stages of cooling of the bodies have already been discussed at length under the heading of serpentinization.

Age of the Ultrabasic Rocks. All of the bodies of ultrabasic rocks have been injected into the Middle Permian succession of sedimentary and volcanic rocks. It has been shown that the intrusion of this magma began while the sedimentary rocks were still flat-lying, or nearly so, so that the formation of the igneous bodies probably took place not long after Middle Permian time.

The Takla series, the lowest part of which is probably Upper Triassic in age, has not been invaded by the ultrabasic rocks, either in the area under discussion or in the surrounding district. In the vicinity of Pinchi Lake, Armstrong (personal communication) found pebbles of serpentine and grains of chromite in a conglomerate of Upper Triassic age.

Ultrabasic rocks are traversed by dykes which are related to granite which intrudes the Takla series, so that the former are definitely pre-granite in age.

The age of the ultrabasics, then, has been established as post-Middle Permian and pre-Upper Triassic, the most likely time being about the close of the Permian, since they had become exposed to erosion in Upper Triassic time.

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DEFINITIONS OF ARKOSE

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ABSTRACT. An examination of the definitions of the term *arkose* in the current literature shows that the rock is described by different writers as 1) a sandstone with a considerable amount of feldspar, 2) a coarse sandstone or fine conglomerate of quartz and feldspar, and 3) a feldspathic sandstone which looks like a granite. In defining the term in 1823, Alexandre Brongniart stressed the high feldspar content as the distinguishing feature of the rock. Thus, definition 1) most nearly agrees with Brongniart's, whereas the other two limit *arkose* to rocks which Brongniart described as varieties of arkose.

WHILE engaged in the preparation of a report on the geology of the Hot Springs area, Madison County, N.C.,[2] the writer found it necessary to reexamine definitions of the term *arkose*. In view of the revived interest in the classification of sedimentary rocks during the last few years, the results of this brief literature study are presented here.

At least three definitions of the term *arkose* are in current usage. In the definition suggested by the Committee on Sedimentation (Allen, 1936, p. 44), arkose is described as "A sandstone containing 25 or more per cent of feldspars usually derived from the disintegration of acid igneous rocks of granitoid texture."[3] Cordier (1868, p. 218) limits the feldspar composition to 10 to 20 per cent of the rock. Krynine (1940, p. 50) sets 30 per cent as the lower limit, but shows the "average" feldspar composition of his "arkose series" as 25 per cent in a later published figure (1948, fig. 11, p. 151). Whatever the proportion used as the lower limit, many geologists (Barton, 1916, p. 418; Coquand, 1857, pp. 236-237; Cotta, 1855, p. 214; Dana, 1863, p. 83; Grout, 1932, p. 275; Hatch, Rastall and Black, 1938, p. 84; Loewinson-Lessing, 1893, p. 18; Milner, 1940, p. 369; d'Orbigny, 1845, p. 140; Pettijohn, 1949, table 55 and fig. 66, p. 227; Shrock, 1948, p. 122; Twenhofel, 1932, p. 229; and Zirkel, 1866, vol. II, p. 526) have accepted the definition of an arkose as a sandstone containing a substantial amount of feldspar and derived from granitic rocks.

[1] The writer is grateful to Messrs. Adolph Knopf, John Rodgers, and Gerald V. Carroll for helpful suggestions.

[2] To be published as a bulletin of the North Carolina Department of Conservation and Development.

[3] Sandstone is defined as a consolidated rock composed of cemented sand grains between 1/16 mm. and 2 mm. in diameter (Allen, 1936, p. 46).

Cayeux (1929) defines arkoses as "very coarse feldspathic or kaolinitic sandstones derived from granitic or gneissic sand" (translated from p. 207). "Arkoses form a transition, by mineral size, between the finer components of pudding-stone [lower limit: 5 mm., pp. 9, 119-120] and sandstone, properly speaking ["5 mm. to 0.5 mm.," p. 124], but with a greater affinity to sandstone than to pudding-stone" (p. 214). Thus the distinction made by Cayeux between feldspathic sandstone and arkose is one of size, not of total feldspar content. Bertrand (1928, p. 448), Dana (1894, p. 82), and Holmes (1920, pp. 36, 282) also limit *arkose* to rocks intermediate in grain-size between psammites and psephites. This definition is supported by that of Omalius d'Halloy (1831, p. 537) which states, in translation, that an arkose is a "conglomeratic rock composed of quartz and feldspar."

De Lapparent (1906) considers arkoses as "rocks formed principally of quartz and feldspar, perhaps with mica, in a manner simulating a true granite, whence the name *decomposed* or *regenerated granite* is given to them" (translated from p. 685). Thus, in addition to requiring that the rock contain a considerable amount of feldspar, de Lapparent and others (Krynine, 1940, p. 50; Murchison, 1867, p. 347; Pirsson and Knopf, 1947, p. 251; and Rosenbusch, 1898, p. 393) impose or suggest the second condition that arkose simulate a granite in appearance.

In view of this divergence in the current definitions of *arkose*, the present writer turned to the original definition of the term by Alexandre Brongniart (1823, pp. 497-498). The term was introduced by Brongniart in an attempt to limit the use of the word sandstone (*grés*), which he felt included too many diverse rocks. He retained the word sandstone for those rocks consisting almost entirely of granular quartz (as distinguished from glassy quartz in quartzites). His definition of the term, literally translated, is, "Arkoses are composed of large grains of glassy quartz and of feldspar, mixed together unequally and including as fortuitous constituents mica, clay, often kaolin, etc."

Why Brongniart chose the word *arkose* is not known. Insofar as the present writer has been able to determine, the word did not exist before 1823. In his original definition of the term, Brongniart (1823, p. 498) does not indicate the derivation of

the term but does say that it is one of the names he has adopted at the suggestion of Omalius d'Halloy. The derivation of the term is not indicated in those publications by Brongniart, Omalius d'Halloy, and other writers available to the writer.

The present writer tentatively suggests that the term *arkose* was taken from the Greek *archaios* meaning ancient or primitive. The points which bear on this view are as follows:

1) Brongniart states (1826, p. 30) that rock names should be derived, with few exceptions, from the "sonorous" Latin and Greek languages and should be easily pronounced by all peoples.

2) Brongniart states (1826, pp. 123-124) that the majority of arkoses studied by him rest directly on granite and indicate ". . . a quite ancient epoch of formation." However, elsewhere in the same paper, Brongniart concludes that there are younger arkoses and age is not implicit in the definition of the term.

3) Brongniart wrote his papers with clarity and in detail. This suggests that he omitted the derivation of the term as superfluous, in view of its similarity to the Greek *archaios*.

4) The use of *k*, rather than *ch* or *c*, in spelling the word is rather curious. Brongniart may have used *k* in preference to the others to insure that the term would be pronounced similarly in French, German, and English, or he may simply have followed the example of Jurine (1806, pp. 373-374), who had previously proposed another rock name, *arkesine*,[4] from the same Greek root.

Brongniart discussed the arkoses more fully in a 51-page paper in 1826. Inasmuch as no statement of his views appears in the modern literature (probably because his publications are not easily available) and as it has a bearing on the present problem, excerpts from his petrographic discussion are translated below. (His views on genesis of the rock, though interesting, do not bear on the problem here.)

> Arkose is a rock of grainy texture formed principally as a result of mechanical aggregation.
>
> It is *composed essentially* of large grains of glassy quartz and grains of lamellar, compact or clayey feldspar: these two minerals are often mixed in more or less equal quantities but more often quartz is dominant. It includes, as *accessory constituents*, mica,

[4] Proposed for the talc- and chlorite-bearing hornblende granite on Mont Blanc, the term is no longer in use.

lithomarge clay, and kaolin, in quantities less than either quartz or feldspar.

The *fortuitous ingredients* (*parties accidentalles*) which are disseminated through the arkose are many [and a list of those minerals which he identified is presented].

This rock has no distinct small scale structure, and rarely even on a large scale, and it is generally thick-bedded.

Its texture is essentially grainy; grains angular, ranging from millet-seed size to pea size. The mass of the rock was evidently formed as a result of mechanical aggregation; the irregular and angular form of the grains and especially their "limitation," such that they do not penetrate one another, is the proof of it . . .

The arkoses, sometimes so distinctly characteristic that one cannot confuse them with any other rock, in some cases present vague, uncertain, or incomplete characteristics.

When the feldspar content is low and the quartz content high, the rock passes into quartzite, if the quartz is glassy, or into sandstone (grés) if the quartz is finely granular . . .

The varieties which are present in these rocks are not numerous and may be reduced to the following:

Common arkose

Composed of glassy quartz and grains of feldspar with very little mica; quartz dominant. Color grayish or whitish . . .

Granitoid arkose

Grains of quartz, of lamellar feldspar and of mica, more or less disposed as in granite; feldspar dominant.

This rock does not differ from granite except that it is evidently formed by aggregation.

Miliary arkose

Grains of quartz and feldspar, as large as millet seeds at the most; disseminated colored clay; quartz dominant; little mica . . . does not differ from common and granitoid arkose except by grain size . . .

It is evident from the excerpts quoted here that Brongniart considered the granitic appearing rocks as one of several forms of arkose. Therefore it appears that the second condition imposed by the de Lapparent definition, i.e. that the rock simulate a granite in appearance, was not considered necessary by Brongniart. Furthermore, the subjectivity of the condition makes it undesirable in modern usage.

Although Brongniart specified "large grains" in his original definition, it is the present writer's belief that it is not an essential part of his definition. This view is supported first by

his making arkose a subdivision of sandstone (1827, p. 43) and second by his defining fine-grained or miliary arkose as one of the varieties of arkose. Therefore, and because the size connotations stressed by Cayeux have not been generally adopted in most countries, it seems unlikely that Cayeux's definition will prove acceptable to most geologists, despite the support it receives from that of Omalius d'Halloy.

Thus, of the three definitions of arkose in current usage, that of the Committee on Sedimentation appears to reflect the meaning intended by Brongniart best and does so in quantitative terms and in conformity with the usage of many geologists. The other two definitions may well be retained for varieties of arkose, in keeping with the procedure of Brongniart himself.

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REVIEWS

Two Problems of Marine Geology: Atolls and Canyons; by PH. H. KUENEN, Pp. 69; 4 pls. Kon. Ned Akad. Wet., Verh. (Tweede Sectie), Dl. XLIII, No. 3, 1947.

I *The Borings of Maratoea Atoll and the Coral Reef Theory of Glacially Controlled Subsidence.*

An important contribution to the study of coral reefs is furnished in the form of quantitative data concerning depth of coral limestone. Two borings were made by the Bataafsche Petroleum Maatschappij on the raised atoll of Maratoea, about 80 km. northeast of Borneo. One hole passed through 261 m. and another through 429 m. of coral limestone and related deposits. The cores are interpreted as indicating a reef margin where coral is interfingering with coral detritus and lagoonal deposits.

After reviewing arguments against theories of atoll formation on stationary platforms, Kuenen suggests that the great thickness of coral indicates upward coral growth during subsidence of an underlying platform. During the Pleistocene lower temperatures halted coral growth in marginal areas of the coral seas and mechanical wave abrasion soon reduced the reefs to platforms graded to the lower sea level. Kuenen suggests that in the central coral seas solution by temporarily undersaturated sea water lowered the elevated reefs while corals continued to grow at the lower sea level. With the subsequent rise of sea level corals grew up from the platforms.

Although this theory of a multiple origin of coral reefs is not new, the subsurface evidence now available gives it much greater importance. However, subsidence at Maratoea may have been local; only additional data will indicate its wider importance. Kuenen's choice of a name for this theory is unfortunate for the subsidence is not glacially controlled as the term indicates.

II *Submarine Canyons and Their Formation.*

Kuenen outlines some known facts concerning submarine canyons and critically reviews seven principal hypotheses of origin. He favors canyon excavation by currents of suspended sediment moving down the continental slope. During the Pleistocene, with lower sea level, large quantities of loose sediment were exposed along coasts which favored development of heavy suspensions by storm waves. Slumping and sliding would be important both in forming the initial furrow and in widening canyons.

Kuenen found experimentally that a heavy suspension of sand released on an underwater slope of 13° attained a speed of 30 cm./sec. He estimates that a velocity of 1 to 4 m./sec. might be expected under natural conditions. At the present it seems to be

but a matter of opinion whether a suspension current of this velocity could erode any but the most loosely consolidated sediments to the extent of the known canyons. DWIGHT R. CRANDELL

Gesteine und Minerallagerstätten. Erster Band: Allgemeine Lehre von den Gesteinen und Minerallagerstätten; by PAUL NIGGLI, with special assistance on Part IV by ERNST NIGGLI. Pp. 540; 335 figs. Basel, 1948 (Verlag Birkhäuser, 42 Swiss francs in paper, 46 Swiss francs in cloth).—This is the first in a projected series, now approaching completion, of three volumes on rocks and mineral deposits. The present volume has been designated as Number 3 in the Mineralogical-Geotechnical Series of Textbooks and Monographs in the Realm of the Exact Sciences, and is concerned solely with some of the fundamental principles of petrology and the science of mineral deposits. In the foreword, the author states that he has found the customary division into igneous, sedimentary, and metamorphic rocks and mineral deposits to be very unsatisfactory, especially in view of the usual lack of preliminary discussion of the basic principles underlying their formation. His chief objection to the three-fold division is based on the resulting development of genetic concepts, which are completely divorced from each other, for each of the three classes of rocks. This volume, therefore, is an attempt to bring these principles together in a new way. Detailed descriptions of rocks and their associated mineral deposits will appear in the two forthcoming volumes entitled "Die exogenen Gesteine und Minerallagerstätten" and "Die endogenen Gesteine und Minerallagerstätten" respectively.

Part I is concerned with the principles of geochemistry and crystal chemistry, and includes descriptions of the most important rock-forming minerals and ore minerals with special emphasis on their atomic structure. Of particular note are the fine photographs of models illustrating the atomic structure of minerals.

Part II, entitled "Das Gefüge," is a detailed treatment of the structure and texture of rocks and ore minerals from both the macroscopic and the microscopic viewpoint. Sections on petrofabric analysis, the application of statistical theory to petrologic problems, and the methods of representing graphically and numerically the mineral and chemical composition of rocks are included. Zoning in crystals, intergrowths, overgrowths, porosity, permeability, corona structures, and the size and shape of grains also are treated. These pages are profusely illustrated with excellent line drawings of a great variety of fabrics.

Part III is a treatise on the physical chemistry of the genesis of rocks and ore deposits. Following the theoretical discussions is a separate section on the important processes in mineral formation.

Part IV discusses the physics of the Earth's outer shell. Numerous tables present the fundamental physical constants of rocks and minerals. A section on applied geophysics describes eight current geophysical methods used in the search for mineral deposits and subsurface structural data.

Part V is a summary of the author's classification of rocks and mineral deposits which will appear in greater detail in volumes II and III of this series. In brief, all rocks and mineral deposits are divided into two major groups, the exogenous and the endogenous. The exogenous rocks and mineral deposits are formed in the border zones of the lithosphere, atmosphere, and hydrosphere. All the sedimentary rocks and all weathering products are included in this category. The endogenous rocks and mineral deposits are those that are formed within the lithosphere. They are subdivided into katathermal rocks and mineral deposits and epi- to mesothermal rocks and mineral deposits depending on the intensity conditions under which they were formed. The katathermal division includes the igneous rocks, high temperature veins, ortho- and paragneisses, migmatites, and the products of high temperature hydrothermal and pneumatolytic alteration. The epi- to mesothermal division includes the rest of the metamorphic rocks, low temperature veins, and the products of low temperature hydrothermal alteration.

There are no references to the periodical literature except in Part IV, Section C, on applied geophysics, but the book contains an extensive list of current reference works.

To the beginning student this mode of presentation will probably prove to be confusing. There is no mention of any connection between particular rock-forming minerals and specific geologic environments. A great many fabrics are carefully described and superbly illustrated, but the genetic implications of the fabrics and the close relationship of many fabrics to specific rock types are not brought out. As a result, the student is faced with a bewildering array of mineral and fabric names that conveys little of geologic significance.

On the other hand, the advanced student will find a great wealth of pertinent information assembled in one volume. Professor Niggli has performed a notable service in presenting the principles of statistics, physical chemistry, and crystal chemistry from the geologic viewpoint.

CHARLES B. SCLAR

ERRATA

In the paper by Donald V. Higgs, August number, p. 582, the cut, figure 5, should have been inverted. P. 583, second reference, should read "Bull. Geol. Soc. America, vol. 60, no. 4."

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